◉ 解　說

Some Considerations on Developments in Reliability, Maintainability and Manning Indices for Engine Systems During the Past 30 Years in Japan – and the Future

일본의 과거 30년간 박용기관시스템의 신뢰성, 정비성 및 매닝인덱스의 발전에 대한 소고와 그 장래

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Abstract

A marine engine system (MES) should be evaluated by not only reliability (R) but also maintainability (M) and manning index (MI), because this system can be recognised as a typical man – machine system. In 1977 at the first ICMES Conference in Paris one of the authors presented a total evaluation of the MES with the three indices, R, M, MI, proving the human ability of detecting faults and defects in this system. This paper describes how the MES has developed from the point of view of the above three indices during the past 30 years in Japan and its problems in the future, and arrives at the following conclusions : the reliability of the MES has developed due to quality control (QC) ; the maintainability of the MES has improved due to education and training ; the manning index of the MES has improved due to Rand M ; the availability of the MES has kept constant due to the decreasing complement onboard, at the rate of one person per year approximately ; and two estimations having the three indices were shown by the SRIC 1990 Data Base in Japan, for the two kinds of subsystems in the developed MES.

Introduction

A marine engineering system(MES) should be evaluated by not only reliability(R) but also maintainability(M) with a manning index($MI = R \cap M$), because this system can be recognised as a typical man - machine one.

In 1977 at the first ICMES Conference in Paris one of the authors presented a multivariate evaluation of the MES with the three indices R. M and MI, proving the human ability of detecting fault and defects in the system.

Approximately 16 years have elapsed since 1977, and many kinds of innovations on ships and many MESs have been developed to overcome lots of problems. These are : how to automate for a smaller complement ; how to treat worse fuel oil ; and how to pursue scale merits for economical return, etc(see Fig 1).

This paper describes the historical developments of three kinds of evaluating indices, ie reliability(R), maintainability(M) and manning index(MI), of MESs with respect to various ship automations during the past 30 years. And two estimation examples are introduced for the central fresh water cooling and mono fuel oil supply subsystems by using the Data Base of the Ship Research Investigation Committee(SRIC) 1990 in Japan.

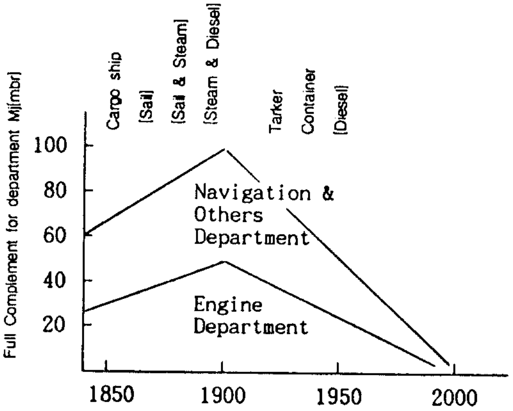

Fig. 1. **Transition in ship complement of engine department during the past 150 years (1850 - 2000) and its future**

Some Innovations on Ships and Their Automation Levels

There have been some innovations on ships, which can be represented by six kinds of automation levels with respect to and multivariate evaluation with three indices of R, M and MI during the last 30 years, are shown in Fig 4 and will be explained as follows.

Multivariate evaluation of MES due to ship automation

The history of ship innovations and ship automation levels, with their complements, has already been explained in the previous sections. Here, some useful evaluations having three kinds of indices, reliability λ, maintainability mh and MI, will be reproduced with respect to the above automation levels.

First of all attention should be paid to the three specialised characteristics curves which connect the three kinds of maintenances(▼▽, ▲△, ■□) shown in Fig 3. They were the MES shown in Fig 2 and the total ship shown in Table Ⅰ. It is very interesting to know the relationship between some automations, for example the automation of hardware, its reliability in a wide sense, and ships complement. It may be true now that the higher level of ship automation has been able to achieve a decreasing complement, shown in Table Ⅰ and Fig 2, after 1950. From the view point of this relationship the automation of two kinds of ship(Ⅳ and Ⅴ) is remarkable due to the following reasons :

1. The fourth level of automation (ship Ⅳ) adopted the progressive redundant system with

Table Ⅰ. History of ships automation levels and their innovations with complement levels

	Level of ship automation	*Innovations with com plement* *Engine*	*Deck*
	Ship Ⅰ	Automation of subsystem	
	Conventional ship	20 15	50
1955	Ship Ⅱ	Local automation of system	
	Semi automated ship	15 13	45
1960	Ship Ⅲ	Bridge control ship	
	Full automated ship	13 8	40
1970	Ship Ⅳ	Unmanned(*NK MO ship) engine	
	Super automated ship	6 8	30
1980	Ship Ⅴ	Distributed computerised ship	
	Ultra automated ship	5 6	20
1988	Ship Ⅵ	Inteligent ship	
	High reliability ship	4 5	11 12
20??	Ship Ⅹ	Complex or simple ship	
	Future ship	?	?

lots of alarms and sensors for a great part of the engine plant, which could achieve and unmanned engine at night (Rules of Nippon Kaiji Kyokai ; MO ship NK) and then reduced the complement number by 5(approximately 40%).

2. The fifth level of automation (ship Ⅴ) could achieve a distributed computerised system for the total ship, which conld also reduce the complements of total ship and engine department by 10 and 2 respectively. This leads to a break in her sections between deck and engine departments of ship Ⅵ. Moreover, these two kinds of ships have cross of mutual relief maintenance systems due to the common work complement onboard.

Total quality control (TQC) and the growth of reiability and maintainability (R&M) should not be forgotten with regard to their contribution to the levelling up and reduction of the complement, some redundant ones being transferred to land. Details for ship Ⅱ are shown in Fig 2.

It will also be interesting to think about the kind of automation and the complement size of the future ship Ⅹ, and whether it is complex or simple.

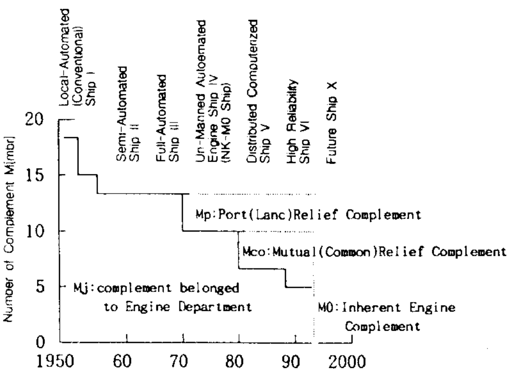

Fig. 2. Transition in ship complement of engine department and ship automation levels during the parst 50 years (1950 - 2000) and their future

It is too vague to investigate the relationship between reliability and complement, therefore some important terminologies for maintenance works(Ti) and for evaluation indices (Dj) are defined and shown in Table Ⅱ for future quantitative analysis and estimation in detail.

History of Ship Innovations and Multivariate Evaluation Indices Due to Automation of Ships Ⅰ - Ⅵ

Here the authors would like to introduce old field data, shown in Fig 3, which also includes a new field one. The former data, presented at the first ICMES Conference in Paris in 1977, refers to surveyed ships built during 1955 1973 and the later data now being presented at this fifth ICMES Conference in Hamburg in 1993, refers to those built during 1983 1988.

According to the above two field data, some ship inovations of MESs with respect to the history of ship automations already presented in 1977 with respect to three levels of ship automation, ie ships Ⅰ · Ⅳ built during

Table Ⅱ Some teminologies Ti and evaluation indices Dj

T1	Running time	Tr = Time on voyage Tv + time in port Tp. Tv is propelling hours.
T2	Emergency maintenance Mz	Maintenance work needed for critical - or major - failure which causes stoppage and slowing down of main engine.
T3	Corrective maintenance Mc	Maintenance work for non - critical failure, which is repairing and unexpected action after any trouble or failure irregularity.
T4	Preventive maintenance Mp	Maintenance work which ensures any preventive action to system against failure due to trouble in condition monitoring, scheduled plan and inspecting action.
T5	Precautionary maintenance Mpr (Ref 14)	Maintenance work which has properties of Mc, Mpr and Mp ; their properties are(1) irregularity with assigned action and (2) regularity with unexpected action.
T6	Inspection action Mai	Inspecting work needed for Mz, Mp and Mpr and on patrol and monitoring of engine system.
T7	Alarm A1	Any announcement which gives an alarm for abnormal and critical conditions included by the rules of Nippon Kaiji Kyokai (NK) for the unmanned engine system at night.
D1	Occurring rate l(occ/1000 or 10,000h)	Total occurrences/assigned running interval 1000 or 10,000h, which is equal to the inverse of mean time between two occurrences(MTBM).
D2	Man - hour per occurrence mh(mh/occ)	Total man - hours consumed onboard/total occurrences during running time, which is equal to the mean man - hours per occurrence.
D3	Manning index($= \lambda \times mh$) MI(mh/1000 or 10,000h)	Total man - hours consumed onboard/assigned running interval 1000 or 10,000, which is equal to $\lambda \times mh$ for maintenance.
D4	Availability A(%)	Up time/(Up time + down time), thich is equal to the average availability and to the total maintenance hours per running time.

1955 - 1973. The field data were submitted from more than 100 vessels during more than 1M hours running time, Tv. These three evaluating indices, with inspection actions(●○), could be obtained, as corresponding statistics, by the analysis of a great number of field data which comprised more than 230 000 maintenance tasks.

It is clear that the maintenance load on the engine department complement of the ship with a higher level of automotion, had beeome less than that of the lower one due to the three characteristics curves. This means that the maintenance load is equal to the MI which sums five kinds of maintenance works : emergency maintenance Mz ; corrective one Mc ; precautionary one Mp ; preventative one Mpr ; and inspection action Mia. Therefore, the less maintenance load means the better is the ship, for any complement could and/or should be evaluated by the lesser MI because this index has both the meaning of R and M as in equation (3), mentioned in the section on evaluation of marine engine systems and its estimation process. The total MI of ship Ⅳ (NK MO classed) with diesel and turbine main engines was 1560 and 1050(mh/1000h) respectively, which was approximately 65 - 45% of that of MI(2290(mh/1000h) of MO classed Di ship Ⅰ.

This first remarkable effect of a smaller maintenance load has been caused by many kinds of innovations which include the well known TQC, adaptation of higher automation with computers and experienced manpower educated by a systematic training programme for higher automation level of ships Ⅰ - Ⅳ.

After 1980 the same tendencies of three automation levels for ship Ⅳ - Ⅵ, shown in the left part of Fig 3, can be seen although there are two kinds of maintenance works which are Mz and Mc. This field data were submitted from 36 vessels classified as ships Ⅳ - Ⅵ dur-

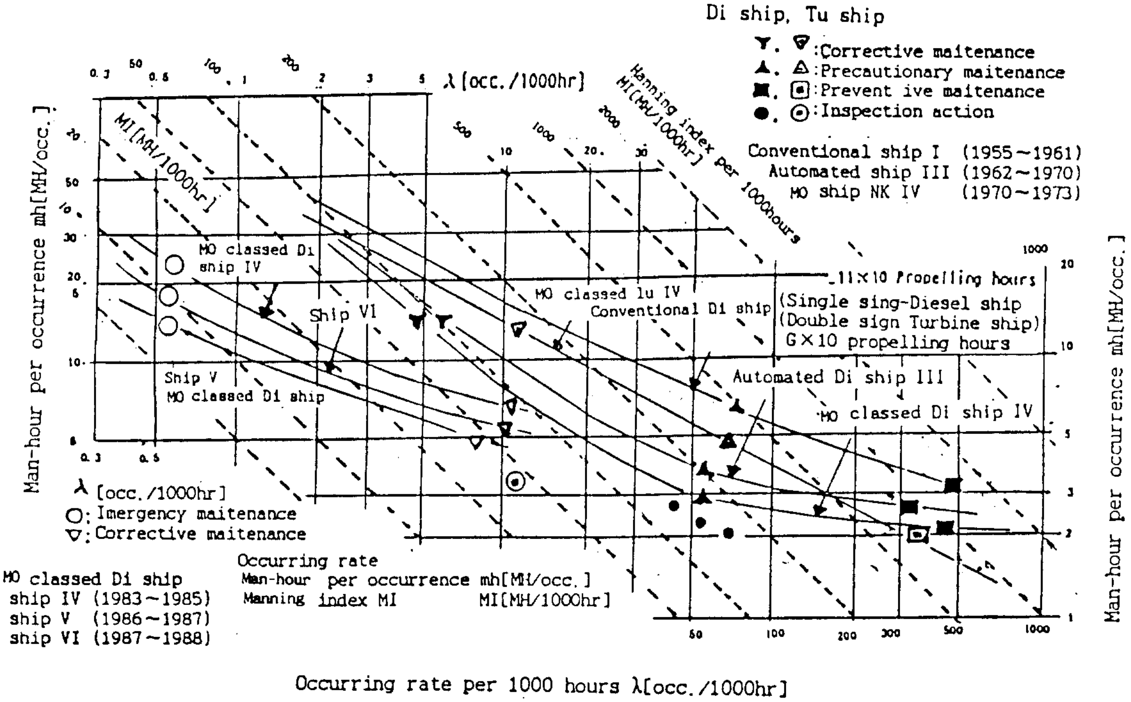

Fig. 3. Multivariate evaluation for MES with reliability l, maintainability mh and manning index MI, with respect to ship automation levels for ships Ⅰ～Ⅵ(1955～1985)

ing 1983～1988. In this case the number of field data is approximately 14,500 maintenance jobs which includes 564 tasks of emergency maintenance.

The total MI is approximately 33,590 (mh/1000h) which includes MIz 10746 (mh/1000h) of emergency maintenance Mz.

Here the authors would like to investigate the corrective maintenance tasks which are common between two period after and before 1980. The MI of ships Ⅳ～Ⅵ after 1980 is approximately 50(mh/10000h) which is less than those of ships Ⅰ～Ⅳ before 1980. The minimum value MI of ship Ⅴ is 40(mh/1000h) which is approximately one quarter of the maximum one of 150(mh/1000h) for ship Ⅰ (conventional diesel ship) and ship Ⅳ(NK MO classed turbine ship) before 1980, with respect to corrective maintenance work Mc.

This second remarkable effect of a lesser maintenance load had been contributed by the following considerations :

1. Compartmentalisation between deck and engine departments and reconstruction of cross or mutual relif system for maintenance work and ship operation onboard, are major factors mentioned in the previous sections.

2. A drastic reduction of the complement onboard must transfer some part of maintenance load onboard to land hands, who are port reliefs and shipyard workers. This maintenance system is the so-called total maintenance system.

History of Three Evaluating Indices for Mes During the Past 30 Years in Japan

The historical evolution of the three evaluating indices for MES of ships Ⅰ～Ⅳ, surveyed during 1955 – 1988, have been described previously.

Only common maintenance work, which is corrective work Mc, can be shown in Fig 4, with its evaluating indices λ, mh and MI(○●, ▽▼, □■ ; diesel ship and turbine one) respectively. The three kinds of symbols are located at the times of each survey year (reference number RX).

Due to the distribution of the three indices (ie, symbols ○●, ▽▼, □■) there are two or three periods. One consists of two periods : before and after 1980 ; the other consists of three periods : before 1970, 1970 – 1980 and after 1980. Now these three periods will be named lst, 2nd and 3rd in order to consider each period in turn.

1. During lst period before 1970 the occurring rate λ had decreased from more than 30 (occ/1000h) for ship Ⅰ to less than 5(occ/1000h) for ship Ⅳ over 25 years. This failure rate tendency was noted by Prof H Tamaki at the last ICMES conference in 1990. The distributions of mh and MI were almost the same as that of λ. These developments could be achieved by the first innovations mentioned in the previous subsection.

2. During 2nd period of 1970 – 1980 some special conditions and circumstances might have occurred in relation to ships and their engine systems. It is well known that there were two oil crises in 1973 and 1978. After 1973 therefore some MI indices and occurring rates λ were approximately 150(mh/1000h), as reported by a turbine ship at R9, and more than 30(occ/1000h), as reported by a diesel ship at R4 respectively, which were much higher than the others. At the same time as the first crisis both the shipbuilder and ship operator had to begin to deal with the problem of worse

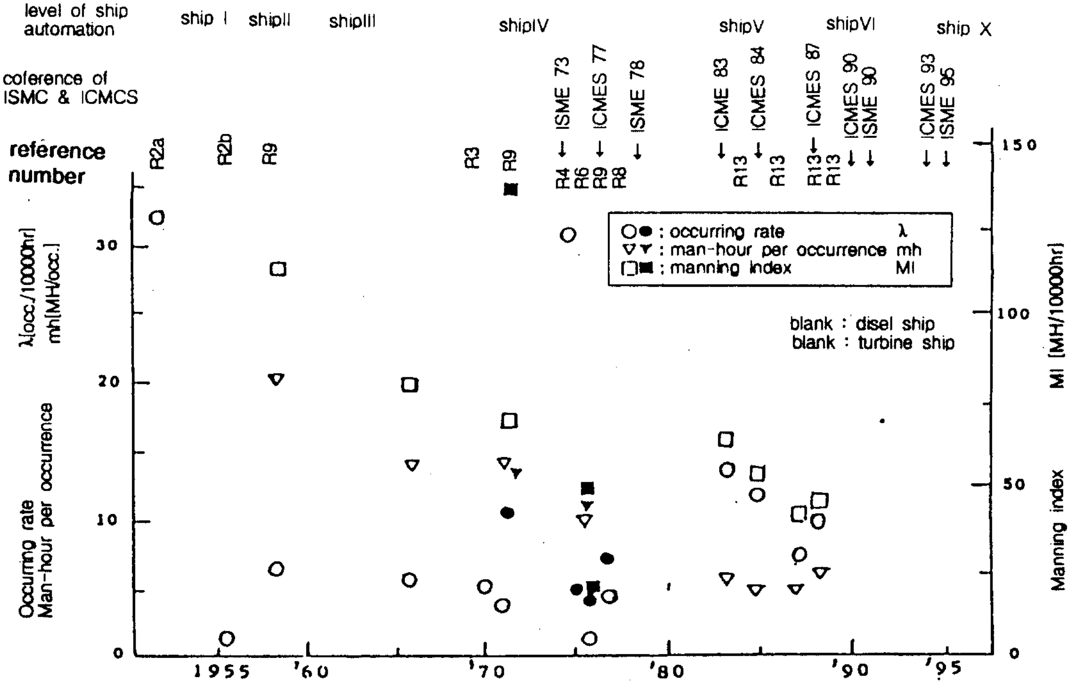

Fig. 4. History of three evaluating MESs during the past 30 years (1955 – 1985) in Japan for ships Ⅰ – Ⅹ ; ie reliability λ (occ/1000h) ; maintainability mh (hm/occ) ; and manning index MI(mh/occ) for corrective maintenance

fuel oil.

3. During 3rd period after 1980, the three kinds of indices gradually decrease to minimum or low levels : 7(occ/1000h)for λ ; 4 (mh/occ) for mh ; and 40(mh 1000h) for MI, respectively. These trends can be achieved by the second innovation due to human factors which is breaking of compartmentalisation and maintenance relief systems, etc.

4. Attention should be paid to the fact that during the second half of 3rd period after 1985, the three indices may be decreasing. This may be due to other abnormal conditions and circumstamces surroundings ships. It would be too difficult for most Japanese shipowners to employ good Japanese seamen and instead they employ non Japanese ones. This fact means that lots of Japanese ships cannot operate well and maintenance on MESs has deteriorated, and therefore reliability and maintainability after 1985 have become worse than before 1980.

Evaluation of MES and Its Estimation Process

Evaluation of MES and its background

There are two methods for evaluating an MES : one is to collect some field data of failures or problems and the other is to use a data base for estimation of a system. The former has already been discussed in the previous sections. This method needs too much field data to collect a lot of information without incurring cost and time, but if there was useful data detailing some apparatus, subsystem or system for evaluating reliabihity and maintenabity indices, then it would be easy to estimate any kind of system from it.

The SRIC Data Base in Japan, which has a large number of field data collected from many kinds of Japanese ships during the past 10 years, is now the most suitable for MESs by using two kinds of statistics which are : failure rate λ and man hours(mh).

The process for evaluating an MES

Here, by using only two kinds of evaluating indices, which are occurring rate λ and mh described in the SRIC Data Base, a simple estimation method for an MES is introduced.

The evaluation process for obtaining one more index, ie manning index MI, besides the abobe two indices λ and mh, is as follows :

1. First of all an objective diagram having some subsystems of any system should be described, whose occurring rate l and man hour per occurrence mh should be given as a marine standard data base like the SRIC Data Base.

3. If an ith higher level system consists of k number of lower level subsystems with n_{ij} number which have lij and mhij then li and MI i of the ith system can be calculated easily by the two following equations :

$$\lambda_i = \sum_{j=1}^{k} n_{ij} \cdot \lambda_{ij} \tag{1}$$

$$MI_i = \sum_{j=1}^{k} n_{ij} \cdot \lambda_{ij} \cdot mh_{ij} \tag{2}$$

and mhi of the ith system by the following equation :

$$mh_i = \frac{MI_i}{\lambda_i} = \frac{\sum_{j=1}^{k} n_{ij} \cdot \lambda_{ij} \cdot mh_{ij}}{\sum_{j=1}^{k} n_{ij} \cdot \lambda_{ij}} \tag{3}$$

4. Finally, the ith three evaluating indices (λ_i, MI_i, mh_i) could be estimated using the SRIC Data Base and then also be plotted on the multivariate evaluation chart like the one shown in Fig. 3.

a. During the evaluation process it was frequently too difficult to pick out the value of λ and mh for the specified items which are objective subsystems and/or apparatuses from the Data Base : in this case alternative item had to be chosen, whose name is very similar and/or a capable one from the Data Base.

b. There are other difficulties in identifying some specifications which are not numbers of sets or units or items but special quantities and/or qualities. They are length and grouped sets like pipes and valves, ratings like output power, and volumes like in small or large apparatuses which canot be described in the Data Base.

c. Moreover, there are no specified kinds of ships and voyage etc, in the Data Base. It should be recognised that those in the Data Base are the most usual and general ones, which means most standard types and systems developed during the survey period of ships Ⅲ and ships Ⅳ in 1960 - 1980.

Moreover, on examination and assessment of the designed system, attention should be paid to the following too :

d. The MI should be recognised as the most useful and important evaluating index among the three evaluating ones because MI has two values for both l and mh shownin equation (3), which makes it necessary to evaluate and assess the designed system for two values of l and mh.

The First Case of Estimation of a Dual Fuel Oil Subsystem(DFOS) and a Mono Fuel Oil Subsystem(MFOS)

Background and problems of DFOS and MFOS

It has been a major problem for both shipbuiders and ship operators to treat marine fuel oil, especially after the two world oil crises. Their problems were to have to use lower grade fuel oil for both main and generator engines subsequently. However, it has been possible for main engines to use the worst heavy fuel oil (HFO) after treatment but generator engines had to use marine diesel oil (MDO) due to their difficulties with lower reliability and durability with HFO. The so - called dualfuel oil subsystem (DFOS) uses two kinds of fuel oils in an MES.

Recently as the problems of smaller engine size and less restrictive conditions on combustions etc, have been overcome by using techniques such as higher viscosity control, purification, straining and anti - sludge, the generator engines have been able to use HFO too. This is called the mono fuel oil subsystem (MFOS) (or uni - fuel oil subsystem UFOS) in comparison with the DFIS.

However, MFOS has been adopted by approximately 16 - 22% of surveyed ships which used HFO, according to the report of No 3 Committee of Machinery Engineering Systems of MESJ and the Research Committee for Outfitting of the Society of Naval Architects of Japan, due to the following reasons :

1. For both independent and historical reasons for main engine and generator engine.

2. In case of adoption of shaft - generator the need for DFOS becomes less.

3. Some problems with DFOS connected with both main and generator engines might cause the vital failure of the ship itself.

4. The poor experience of shipowners may discourage them from adopting MFOS due to some remaining problems which are a lower reliability of exchange of MDO from HFO for generator engine at main engine stoppage.

5. The performance of MFOS is poor com-

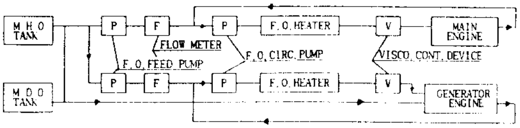

Fig. 5a. A typical flow diagram of conventional fuel supply system ; ie dual fuel oil subsystem (DFOS).

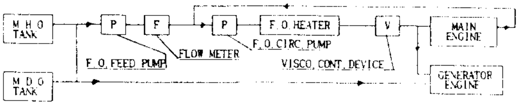

Fig. 5b. A flow diagram of proposed fuel supply subsystem, ie mono fuel oil subsystem (MFOS)

pared to its cost effectiveness.

However MFOS has some advantages which are simplicity of the subsystem and less maintenance, these advantages might overcome the above problems. The authors have also been trying to make quantitative evaluations for reliability and maintainability of DFOS and MFOS as follows.

Outline of flow diagrams for DFOS and MFOS

The models applied to comparable evaluations for maintainability of DFOS and MFOS and indicated in Figs 5a and 5b.

Figure 5a shows a typical flow diagram of a conventional dualfuel oil supply substs tem (DFOS) applied to 90,000t tankers and Fig 5b shows a flow diagram of the proposed mono fuel oil supply subsystem (MFOS) based on the same type of ship.

Estimation of three evauating indices for DFOS and MFOS

In Table Ⅲ the data for three indices λ_i, mh_i and MI_i for each equipment item applied to the oil supply subsystems are tabulated in the left column, which refers to the SRIC Data Base.

Only tow equipments which are items 504 and 510 can obtain their original indices l_{ij} and mh_{ij} directly from the data base, the others

Table Ⅲ. Input data base and estimated results for three evaluation indices l, mh, MI of dual fuel oil subsystem(DFOS) and mono fuel oil subsystem (MFOS)

No	Machinery	λij (Occ x 10 4h	mhij (mh/ occ)	MIij (mh x 10 4h)	nij (set)	Conventional DFOS nijλij(Occ x 10 4h)	MIij(mh x 40 4h)	mhij (mh/occ)	Proposed MFOS nij (set)	nijλij(Occ x40 4h)	MIij(mh x40 4h)	mhij (mh/occ)
501	FO feed pump	0.0388	5.1	0.1979	2	0.0776	0.40	5.1	2	0.0776	0.40	5.1
502	FO circ pump	0.0388	5.1	0.1979	2	0.776	0.40	5.1	2	`0.0776	0.40	5.1
503	FO heater	0.0452	4.9	0.2264	2	0.0924	0.45	4.9	2	0.0924	0.45	4.9
504	Visco cont device	0.0119	4.5	0.0536	1	0.0119	0.05	4.5	1	0.0119	0.05	4.5
505	DO supply pump	0.0388	5.1	0.1979	1	0.0388	0.20	5.1	1	0.0388	0.20	5.1
506	G/E viso cont device	0.0119	4.5	0.0536	1	0.0119	0.05	4.5	0	0.0000	0.00	0.0
507	G/E FO feed pump	0.0388	5.1	0.1979	2	0.776	0.40	5.1	0	0.0000	0.00	0.0
508	G/E FO circ pump	0.0388	5.1	0.1979	2	0.0776	0.40	5.1	0	0.0000	0.00	0.0
509	G/E FO heater	0.0452	4.9	0.2264	2	0.0924	0.45	4.9	0	0.0000	0.00	0.0
510	Valves, pipes etc *1	2.0740	2.1	4.3554	1	2.0740	4.36	2.1	0.85	1.7629	3.70	2.1
	Total(l i, MI i), Average(m h i)				16	2.6318	7.16	2.7	8.85	2.0612	5.20	2.5

Remarks :

1. Input data of λ_i and mh_i for each machinery item refer to the SRIC Data Base 1990 in Japan.
2. For the machinery which is not described in the SRICD Data Base 1990, applicable data are tabulated referring to the other corresponding machinery item.
3. The figures of n_{ij} for the piping and valves are applied as follows :

(*) Valves, pipes, etc(item 510) of DFOS whose length and sets are 440m and 94 sets in total corresponding to normalised 1.0 unit, and the same of MFOS are 425m and 94 sets corresponding to 0.85 unit [=425/444] + [69/94]) /2] .

cannot. They are classified into two groups, which are items 501, 502, 505 – 508, as other corresponding categories are auxiliary pumps and 503 and 509 are heaters.

Estimating results for maintainability of DFOS and MFOS

In Table Ⅲ, the estimated results of three indices λ_i, mh_i and MI_i for both comparable subsystems DFOS and MFOS are tabulated and the relationships between three indices for both subsystems are plotted in Fig 6.

Using this data, the following quantitative results for the multivariate evaluations of DFOS and MFOS are observed :

1. Total manning index MI_i and occurring rate λ_i for the DFOS and MFOS results in 7.16 and 5.20(mh/10,000h) and 2.643 and 2.06 (occ/10,000h) respectively. This means that the proposed subsystem MFOS can save approximately 30% of the maintenance load of the conventional DFOS due to both the elimination of the four items 506 509 and a reduction of 0.85 units of item 510 on the list of MFOS shown in Thable Ⅲ.

2. The remarkable effect of a lower maintenance load of MFOS is due to item 510, ie pipes, valves etc, because its occurring rate λ_{ij} and manning index, MI_{ij} are approximately 80% of the total λ_i and MI_i, respectively. This means that λ_{ij} of item 510 is extremely high, ie 2.07(occ/10,000h) which is 70 – 100 times those of others, ie 0.01 – 0.03(occ/10,000h), although this mh_i is the least, ie 2(mh/occ) which is half of the others.

3. The figure of 0.85 units of item 510 of MFOS is obtained by an average of the weighted reducing effects of length of pipes and number of valves, which is equal to {([425/444] [m] + [64/94] [sets])/2} shown below Table Ⅲ. This means that the occurring rate l_{ij} of 2.074(occ/10,000h) obtained from the SRIC Date Base corresponds with 1.0 unit of item 510 of DFOS in this study.

The Second Case of Estimation of a Seawater Cooling Subsystem(SWCS) and a Central Freshwater Cooling Subsystem(CFWCS)

Background and Problems of SWCS and CFWCS

Applied recently to some cases in marine applications, the central freshwater cooling

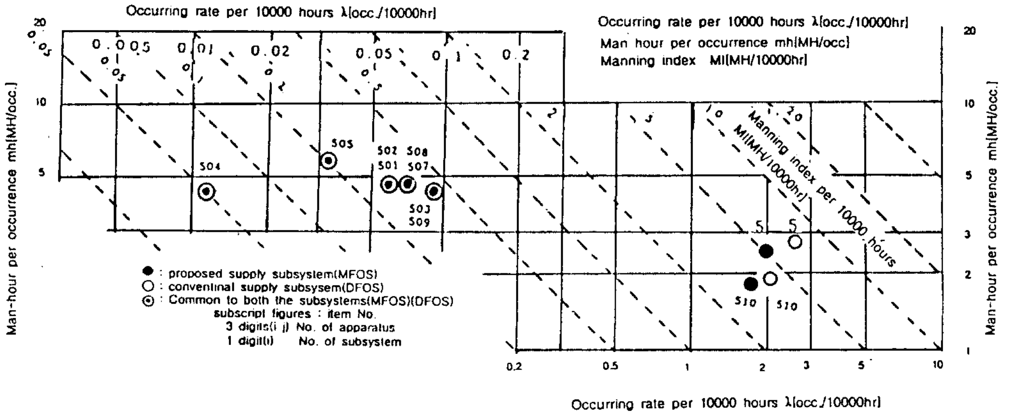

Fig. 6. Multivariate evaluation for MES with reliability λ, maintainability mh and manning index MI of the two fuel oil supply subsystems DFOS and MFOS

subsystem(CFWSC) has been applied to the MES instead of a conventional seawater cooling subsystem(SWCS).

The most obvious reason for the above trend is to reduce the corrosive circumstances due to seawater by replacing the cooling medium by non-corrosive fresh water. Every ship might be affected by such problems as corrosion, leaking and choking which are all very difficult to prevent due to the natural corrosive characteristics of seawater.

On the other hand, according to the results of research into NKK(Nippon Kaiji Kyokai) classified ships, the number of ships applying CFWCS is few, approximately a 9% average for three years from 1989 - 1991 in Japan.

And also, as a result of a questionnaire to several Japanese shipowners which was researched by the Machinery Engineering System Committee in Japan, approximately 30% of owners concerned still hesitate to apply the CFWCS because of its much higher inital cost compared to SWCS. Furthermore, at a point in the life cycle cost for the cooling subsystem, even for the owners who were applying CFWCS to their spips, spproximately 55% of them could not obtain a definite advantage of the life cycle cost with CFWCS, although they could stop man-hours expanding for maintenance work on the cooling subsystem onboard the ship.

Thus, when people concerned with shipbuilding are making plans for the cooling subsystem, they always face the difficult choice between two contrasting conditions, ie higher initial cost or less maintenance work with SWCS.

In order to clarify the above problem, it seems that further definite evaluations for reliability and maintainability of cooling subsystems are required. The authors have been trying to make quantitative evaluations for reliability and maintainability of CFWCS and SWCS as follows.

Outlines of flow diagrams for SWCS and CFWCS

The models applied to comparable evaluations for maintainability of SWCS and CFWCS are indicated in Figs 7a and 7b.

Figure 7a shows a typical fow diagram for a conventional cooling subsystem SWCS applied to a 40,000t bulk carrier and Fig 7b shows a flow diagram of the proposed cooling subsystem CFWCS based on the same type of ship.

Estimation of three evaluating indices for SWCS and CFWCS

In Table IV the data for three indices λ_i, mh_i

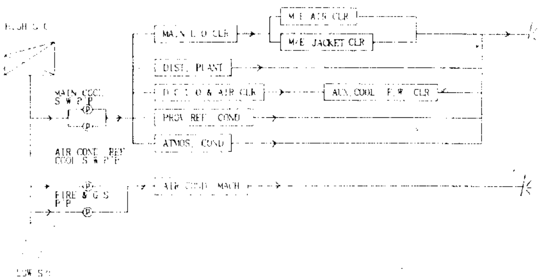

Fig. 7a.A typical flow diagram of conventional cooling subsystem ; ie seawater cooling subsystem (SWCS)

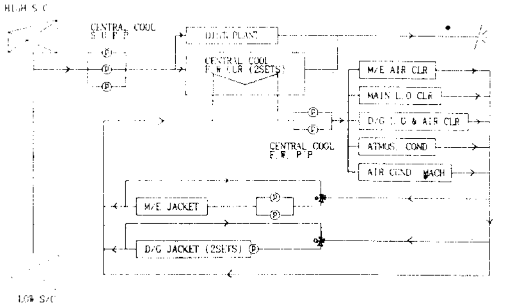

Fig. 7b.A flow diagram of proposed cooling subsystem ; ie central freshwater cooling subsystem (CFWCS)

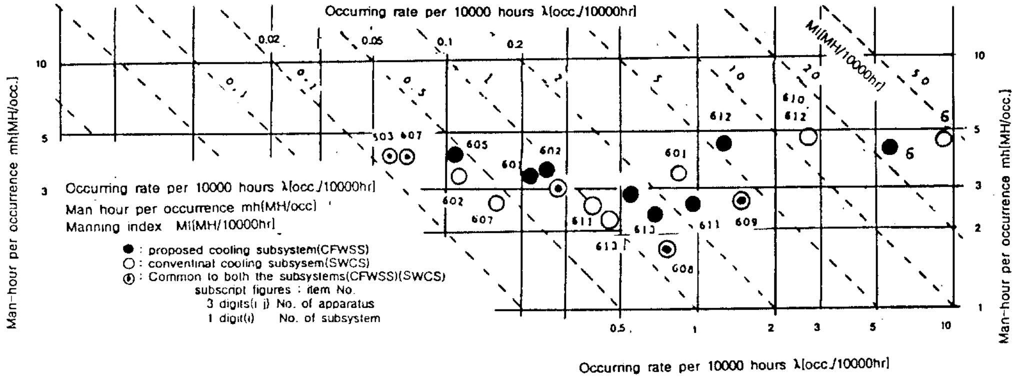

Fig. 8. Multivariate evaluation for MES with reliability, maintainability and the two cooling subsystems, SWCS and CFWCS

and MI_i for each equipment item applied to the cooling subsystems, are tabulated in the left column, which refers to the SRIC Data Base.

In this case only four equipments, which are items 603 - 605, cannot get their original indices directly from the data base but can use the alternativeindices λ_{ij} and mh_{ij} of 0.0576 (occ/10000h) and(mh/occ) respectively, obtained indirectly from the most capable items belonging to one group.

However, the others, which are items 601, 602, 606 and 608 - 613 can get their original indices λ_{ij} and mh_{ij} directly from the SRIC Data Base.

In the case of the last four, they are divided into two groups which are seawater and freshwater. Because the indics λ_{ij} and mh_{ij} of the former group are 2.95(occ/10,000h) and 4.5 (mh/occ) respectively, they are approximately six times and twice those of the latter one.

Estimating results for maintainability of SWCS and CFWCS

In Table Ⅳ, the estimated results of three indices λ_i, mh_i and MI_i for both comparable subsystems SWCS and CFWCS are tabulated. Furthermore, the relationships between the three indices for both subsystems are plotted in Fig 8.

Using this data, the following quantitative results for the multivariate evaluations of SWCS and CFWCS are observed :

1. Total manning index MI_i and occurring rate λ_i for the SWCS and CFWCS results in 39.09 and 22.72(mh/10,000h) and 9.62 and 6.36 (occ/10,000h) respectively. This means that the proposed subsystem CFWCS can save approximately 45% of the maintenance load of the conventional SWCS due to both the elimination of item 604 and a reduction 0.20 units and 0.46 units of items 610 and 612 respectively on the list of CFWCS shown in Table Ⅳ.

2. According to the SRIC Data Base, the occurring rate λ_{ij} for seawater unit(items 610 and 612 shown in Table Ⅳ) is 2.96(occ/10,000h), which is approximately 5 - 50 times that of the others which is 0.45 - 0.058(occ/10,000h) for the freshwater unit(item 611 and 613). Therefore, some drastic improvement of λ_i and MI_i, by means of reducing the length of the pipeline(item 610) and the number of valves (item 612), will be expected for both the subsystems SWCS and CFWCS.

3. While the length of freshwater pipes and number of freshwater valves for items 611 and 613 of CFWCS increased to 2.23 and 1.63 units

Table Ⅳ. Input data base and estimated results for three evaluation indices l, mh, MI of dual fuel oil subsystem(SWCS) and central freshwater cooling subsystem (CFWCS)

					Conventional DFOS				Proposed MFOS			
No	Machinery	λij (Occ x 10 4h	mhij (mh/occ)	MIij (mh x 10 4h)	nij (set)	nijλij(Occ x 10 4h)	MIij(mh x 40 4h)	mhij (mh/occ)	nij (set)	nijλij(Occ x40 4h)	MIij(mh x40 4h)	mhij (mh/occ)
601	Seawater cooling pump	0.2188	3.7	0.8096	4	0.8752	3.24	3.7	3	0.6564	2.43	3.7
602	Fshwater cooling pump	0.0624	3.7	0.2309	2	0.1248	0.46	3.7	4	0.2496	0.92	3.7
603	Lub oil cooler	0.0576	4.2	0.2419	1	0.0576	0.24	4.2	1	0.0576	0.24	4.2
604	Visco cont device	0.0119	4.5	0.0536	1	0.0119	0.05	4.5	1	0.0119	0.05	4.5
605	Central fresh water cooler	0.576	4.2	0.2419	0	0.000	0.00	0.0	2	0.1152	0.48	4.2
606	M/E air cooler	0.2950	3.2	0.9440	1	0.2950	0.94	3.2	1	0.2950	0.94	3.2
607	Other auxiliary coolers	0.0576	4.2	0.2419	3	0.1728	0.73	4.2	1	0.0576	0.24	4.2
608	Air cond unit for accom	0.5314	5.3	2.8164	1	0.5314	2.82	5.3	1	0.5314	2.82	5.3
609	Prov refrigerating unit	0.7222	2.4	1.7333	1	0.7222	1.73	2.4	1	0.7222	1.73	2.4
610	Seawater piping *1	2.9462	4.5	13.2579	1	2.9462	13.26	4.5	0.20	0.5892	2.65	4.5
611	Freshwater piping *1	0.4487	2.4	1.0769	1	0.4487	1.08	2.4	2.23	1.0006	2.40	2.4
612	Seawater valves *2	2.9462	4.5	13.2579	1	2.9462	13.26	4.5	0.46	1.3553	6.10	4.5
613	Freshwater valves *2	0.4487	2.4	1.0769	1	0.4487	1.08	2.4	1.63	0.7314	1.76	2.4
	Total(l i, MI i), Average(m h i)				18	9.6264	39.07	4.1	18.52	6.3615	22.72	3.6

Remarks :

1. Input data of **l** i and m h i for each machinery refer to the SRIC Data Base 1990 in Japan.

2. For the apparatus which are not described in the SRICD Data Base 1990, applicable data are corresponding machinery item.

3. The figures of n i j for the piping and valves are applied as follows :

a. Seawater pipe(item 610) of SWCS is 390m in total corresponding to normalised and the same of CFWCS is 77m corresponding to 0.22 unit(= 77/330) accordingly ;

b. The number of seawater valves(item 612) applied to SWCS is 41 in total and the same CFWCS is 19 corresponding to 046 unit(= 19/41) accordingly

(see remarks (*1) and (*2), shown in Table Ⅳ), the influence of λ_{ij} and MI_{ij} is very small because of the higher reliability of the fresh water item whose original λ_{ij} is only 0.4487 (occ/10,000h).

4. Concerning equipment such as pumps and coolers, their installed numbers in the subsystem immediately result in both total evaluating indices λ_i and MI_i too.

Conclusions

Making a survey of some trends in the transition of ship automation levels and complements on ships Ⅰ – Ⅳ during the last 50 years, and the multivariate evaluation of MES during the past 30 years gives the following results :

1. The complement level onboard has been decreasing gradually from 100 to 10 since the beginning of this century till 1990, due to many kinds of technical innovations.

2. The complement level of the engine department especially, has also been decreasing steadily from 20 to 4 from 1950 1990, due to seven levels of ship automation.

3. It is well known that the fourth level of automation on ship Ⅳ had seen the biggest reduction in the complement level by 5, due to the redundant system with alarms by the rules of NK, who allowed an unmanned engine system at night.

4. Moreover, the fifth level of automation on ship Ⅴ, with a distributed computerised system, could also reduce the complement of total ship and engine department by 10 and 2 respectively, due to ending the ship′s compartmentalisation and introducing cross or mutual relief(common) system onboard.

5. Evaluation of the three indices : (1) reliability λ ; (2) maintainability mh and (3) manning index MI during the past 30 years has resulted in the following :

a. *Reliability l(occurring rate per running time*[*(occ / 1000h)*]. Occurring rate λ, which means a reliability index in a narrow sense, has gradually decreased from about 30 (occ/1000h) in 1950 to a few in 1980, due to the multi-effects of the TQC in Japan. However, after 1985 this index has jumped up to the level of 10(occ/1000h).

b. *Maintainability mh* [*man-hour per occurrence*[*(mh / occ)*]. Man-hour per occurrence mh, which means also a maintainability index in a narrow sense, has gone from about 20 (mh/occ) in 1950 to less than 8 (mh/occ) in 1980 as well as λ. On the other hand, after 1985 this index has increased to 7(mh/occ) in 1988, having a minimum value of 3(mh/occ) in 1983.

c. *Manning index MI(total man-hour per running time(mh / 100h*. Manning index MI, which means a maintenance load for the complement in a wide sense, has two meanings for two original indices λ and mh as shown in equations (1) and (3), only this index has decreased from approximately 150(mh/1000h) in 1955 to 40(mh/1000h) in 1988.

6. After 1985 it was too difficult for most Japanese ship owners to employ good Japanese seamen and they had to employ non-Japanese ones. Consequently, not only good operation but also good maintenance could not be obtained for the MES and therefore reliability and maintainability after 1985 became worse than what they were before 1980.

By only using two statistics(occurring rate λ and mean man-hour mh) from the SRIC Data Base 1990 in Japan, the two examples of estimation for the fuel supply subsystem and water cooling subsystem could be used to obtain the third index, ie manning index MI, besides λ and mh. These two examples(MFOS and CFWCS) of estimation give the following results :

7. Both examples of estimation are very useful so that the following conclusions can be reached :

a. First of all it is useful to utilise the SRIC Data Base for estimation of the evaluation indices(λ, mh, MI).

b. It has been proved that both the proposed subsystems could save 30% and 40% of the total manhours, ie 7 and 40(mh/10,000h) for MFOS and CFWCS respectively, in comparison with those of conventional ones, and in the case of CFWCS seawater pipes and valves take up the majority of total man-hours too.

8. According to item 7 above the manning index MI is very important in designing not only a more reliable but also a more maintainable system, by assigning and saving some limited assets to any subsystem other than the other two indices λ and mh.

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