Risk Assessment and Life Cycle Support of LNG Carriers

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The operational environment of LNG carriers is changing due to various factors including increased demand for LNG, changes in LNG transactions and modes of operation. Though LNG carriers have a higher safety level record than other types of ships, the risk levels of LNG carriers are to be more precisely assessed considering these changes, in order to propose, study and evaluate proactive safety measures for the future. This paper presents details on a project that ClassNK has been undertaking for the risk assessment of LNG carriers with respect to hull structures, propulsion machinery, and in turn life cycle support with emphasis on advanced risk management that encompass fatigue and corrosion.

KEY WORDS
Risk; Assessment; LNG; Lifecycle; Fatigue; Corrosion; Sensors

INTRODUCTION

Since natural gas is emerging as a cleaner energy source, and more and more natural gas development projects are on the anvil, marine transportation of natural gas will be on the increase in the future. In order to achieve a safe and stable operation of LNG carriers, maintaining the ship's integrity on hull structure and equipment at a certain safety level while minimizing the required life cycle cost would be a key issue.

In the turbulent market conditions where orders on newbuildings are partially on hold, it is a prudent option to extend the life of existing vessels so as to use them for longer years than they are initially intended for. For high value ships such as LNG carriers, this is especially the case where the industry attempts to keep the well-maintained existing fleet in extended service beyond their originally anticipated design lives. Moreover, a much longer design life than conventional ships is being considered for new ships.

LNG carriers have a much higher level of safety record than other types of ships. However, their operational environment is changing rapidly due to a host of reasons, including increased demand for LNG, changes in LNG transactions, and changes in the mode of operation of LNG carriers, amongst others. This necessitates a closer look at the risk assessment of LNG carriers as various risk levels for LNG carriers are to be estimated taking into account such changes, in order that proactive safety measures can be studied and evaluated.

With this in mind, ClassNK have initiated a research project to evaluate the application of various risk assessment methodologies in different areas such as the hull structures, propulsion systems, etc. of a ship, as part of an overall plan to establish an organizational mechanism which would enable risk assessment of any area of the ship. Parts of this project are still ongoing and an outline of the project along with details of the components of the project is given in this paper.

In maintaining a ship with an extended life or a new ship designed with a longer design life, a proper implementation of an effective maintenance plan, developed based on an accurate monitoring of the deteriorating condition, and a reliable assessment of residual life and strength, in addition to a refined inspection and survey scheme, is essential. This project effectively supports the client in the development of an optimized maintenance plan based on risk assessment and life cycle cost assessment.

Further a brand-new advanced ship maintenance support service program, which will result in the practical realization of the ClassNK PrimeShip Total Lifetime Ship Care concept, is briefed with a particular focus on fatigue and corrosion, the essential factors in aging of ships. Of particular note is an application of newly developed sensors to quantify fatigue accumulation and paint deterioration, enabling a reliable estimation of the potential risk levels. The new proposal also includes various features of a comprehensive approach to assist in-service maintenance of ships using leading edge technologies.

RISK ASSESSMENT OF LNG CARRIERS

The LNG operational environment is rapidly changing, and some of the reasons that contribute this change are as follows:

- Expansion of LNG market and increase in the number of LNG carriers. Currently there are about 200 LNG carriers in operation and about 140 on order.
- Entry of new ship operators into the LNG field.

- Increased ship size.
- Increase in spot chartering contract, etc.

These changes raise economic issues, environmental issues as well as manning issues. For example, there is a shortage in the number of ship personnel who can handle turbines common for LNG carriers. Therefore it is imperative that the risk levels of LNG carriers are estimated more precisely to reflect these changes so that proactive safety measures can be formulated, studied and evaluated.

ClassNK is actively pursing this task in an extensive ongoing research project which currently deals risk assessment of LNG carriers with respect to hull structures and propulsion systems.

Risk Assessment of Hull Structures

The main objectives of the risk assessment of hull structures are to estimate the anticipated changes to the safety level of LNG carriers, and to investigate proactive measures to maintain the highest safety level for LNG carriers focusing on hull structures. The risk assessment is conducted following FSA methodology developed by the IMO and illustrated in Fig. 1.

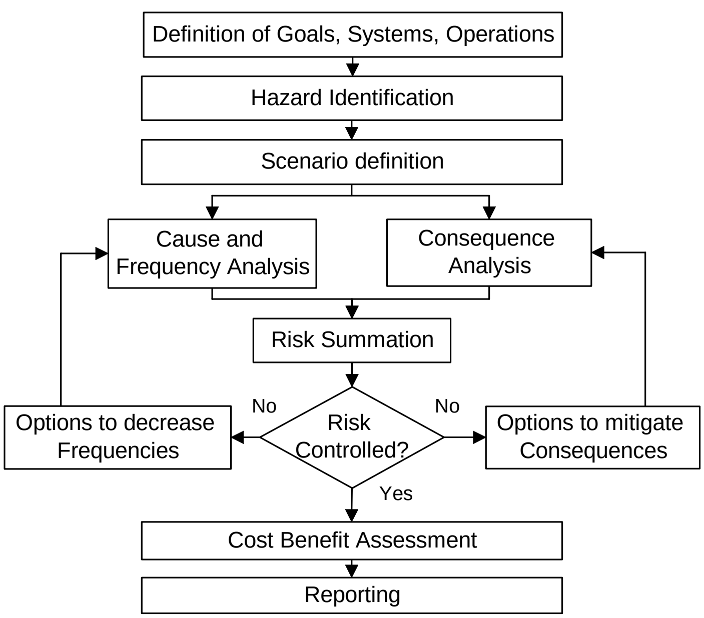


Fig. 1 Flow chart of risk assessment in terms of FSA

The LNG operational environment after ten years is estimated based not only on the anticipated market change but also on historical casualty data etc., and hazard identification exercise was conducted by means of HAZID meeting attended by a multidisciplinary group of experts. In this step, the scope was extended to cover not only hull structures but also other LNG elements such as machinery. It should be noted that this scope expansion helped to conduct risk assessment of propulsion systems described in the next section. Accordingly, identified hazards were prioritized in terms of risk associated with hazard and possible accident scenarios.

In the next step, risk analysis was carried out in accordance with prioritized accident scenarios in order to estimate the change in risk level of LNG carriers about ten years later. Accordingly, an estimation of the change in risk level is being investigated in conjunction with the identification of probable new risks that arise due to the changes.

The near final step would be to take effective measures to control the risks as a countermeasure to an increase in the risk level or new risk arisen in the future as shown in Fig. 2.

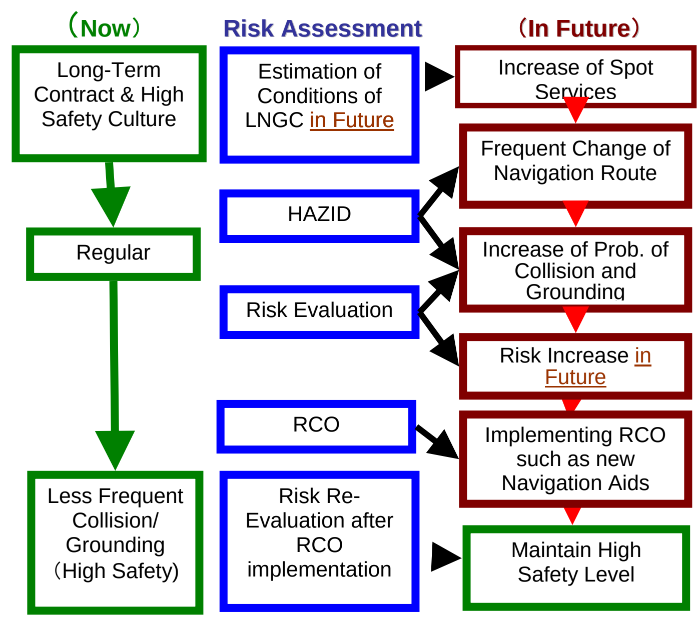


Fig. 2 Conceptual example of risk assessment flow

Risk Assessment of Propulsion Systems

Until now, steam turbines have been predominantly used for propulsion systems of LNG carriers because boil-off gas (BOG) can be used as fuel for boilers. In recent years, however, studies have been carried out on oil-fired diesel propulsion engines with re-liquefaction units, electric propulsion systems using dual-fuel diesel generator engines, and on dual-fuel diesel propulsion engines instead of steam turbine propulsion systems. Some of these systems are already in service.

Table 1 shows the configuration of different propulsion plants. Although BOG can be fully utilized only by the main boiler and dump condenser in steam turbine systems provided with the same equipment, in other systems, the complete system is constructed by combining re-liquefaction unit, BOG combustion unit and other components as required.

Table 1 Configuration of propulsion plant for LNG carriers

Prime mover	Steam turbine, 2-stroke diesel engine, 4-stroke diesel engine, Gas turbine
Fuel	Dual fuel (gas and fuel oil), Mono fuel (HFO)
Drive type	Engine drive, Propulsion motor drive (Electric propulsion)
BOG treatment equipment	Boiler, Dual fuel diesel engine, Re-liquefaction unit, GCU (Gas combustion unit)

In the current study, the following 4 types of propulsion plants are considered:

(a) Steam turbine propulsion plant
(b) Oil-fired (2-stroke) diesel engine propulsion plant with re-liquefaction unit
(c) Electric propulsion plant using (4-stroke) dual fuel diesel generator engines
(d) Dual fuel (2-stroke) diesel engine propulsion plant

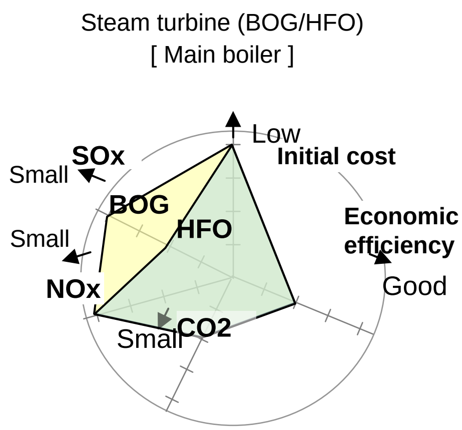
New propulsion plants of (b) to (d) have low reliability compared with steam turbine plant of (a). Further more, an electric propulsion plant using DFD generator engines has comparatively low maintainability, because this plant has in general 4 sets of DFD generator engines and total numbers of cylinders of these engines become large. Low maintainability is also seen in a dual fuel diesel engine propulsion plant. This is because, this plant has high pressure pipe line system of 250-300 bar and leaks from this pipe line and the attachment cannot be ignored.

Propulsion plants are assessed based on the initial cost, economic efficiency, environmental impacts, reliability, redundancy of the components, maintainability, availability of fuels, and securing of engineers. Figures 3 and 4 show the comparison of these factors for the four propulsion plants mentioned above.

Redundancy of propulsion engine for LNG carriers is required in practice because of their special features, as shown below.

(a) Regular operation required as part of the LNG supply chain
(b) Requirements of stand-by of a propulsion engine while at terminal

Furthermore, redundancy of BOG treatment equipment is required according to IGC Code. To make clear the details of such redundancy, ClassNK are now carrying out the risk assessment on several redundant systems, and the interpretation will be released either as a Guidance to the Rules or into a separate Guideline.



2D:	2-stroke diesel engine for propulsion
2DFD:	2-stroke diesel engine for propulsion
4DFD:	4-stroke diesel engine for power generation
PM:	Propulsion motor
[...]:	BOG treatment equipment
DFD:	Dual fuel diesel
RL:	Re-liquefaction unit
GCU:	Gas combustion unit

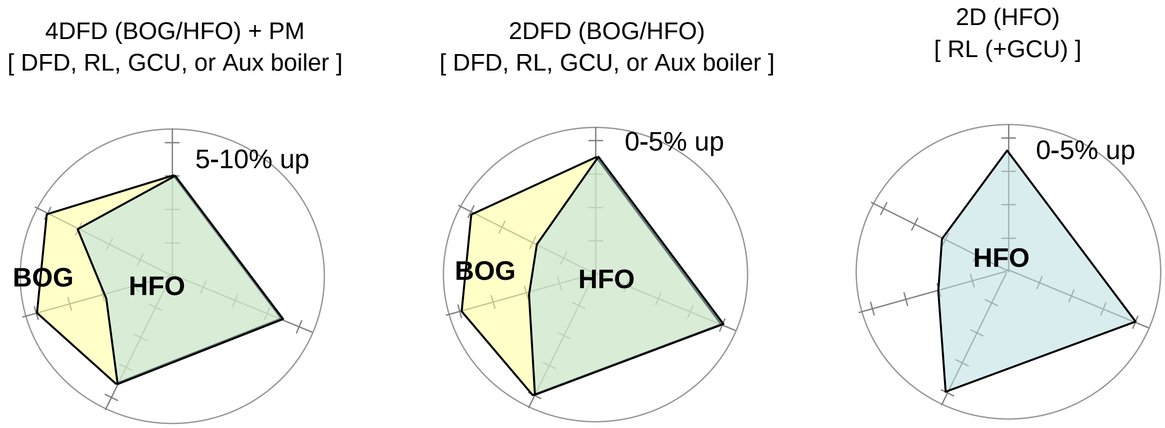


Fig. 3 Comparison of propulsion plants (1)

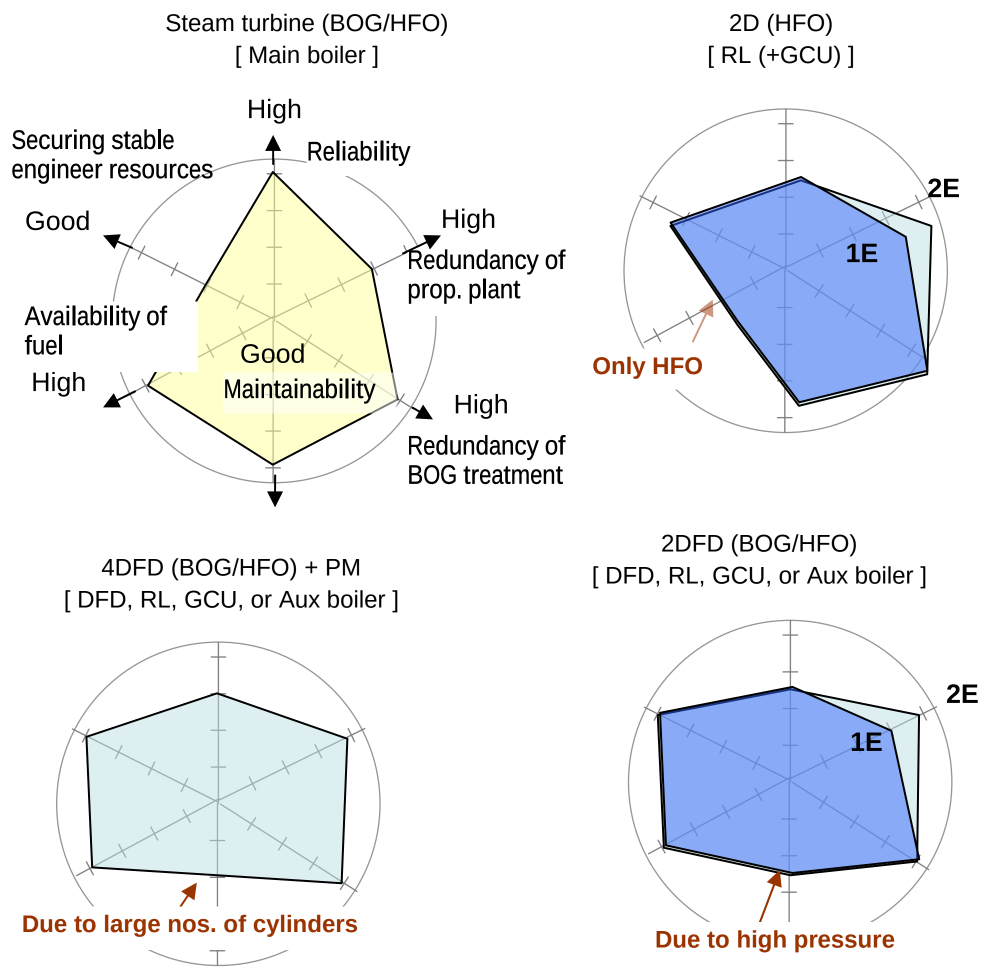


Fig. 4 Comparison of propulsion plants (2)

LIFE CYCLE SUPPORT OF LNG CARRIERS

LNG carriers, which are the dominant, safe and reliable means of transport of natural gas, are now entering a new era of longer operational service lives. While consideration is being given to designs and plans for the construction of new ships with design lives significantly longer than those of conventional ships, the industry also is seeking to keep the currently well-maintained existing fleet in extended service beyond their originally anticipated design lives for as long as reasonably possible.

The safe and stable operation of LNG carriers with such longer life spans requires that the integrity of the ship's hull structure and equipment be maintained to a high level of safety while minimizing the life cycle cost necessary to keep the vessel in good operating condition. Realizing an optimum balance between these two vital goals is a key issue to the successful extension of LNG service life.

A rationally developed and implemented maintenance plan is an essential component to realizing these goals. To be effective, such a plan needs to be based on accurate monitoring of the current state of deterioration of various structures throughout the vessel, a reliable assessment of the residual life and strength of such structures, and the ship as a whole, combined with a refined inspection and survey scheme to keep the ship in good operating condition.

ClassNK is currently developing a brand-new advanced ship maintenance support service program which will result in the practical realization of the PrimeShip-TLC (Total Lifetime Ship Care) concept. This new advanced ship maintenance support service is aimed at reducing the risk and life cycle costs of LNG carriers in service, and to supporting the optimal maintenance of ship structures and machinery equipment against aging factors such as fatigue and corrosion, thereby assisting ship owners and managers more effectively and rationally to deal with the age related problems of LNG carriers. This is accomplished through the application of state-of-the-art technologies and technical expertise to help clients develop optimized maintenance plans based on rational risk assessments mentioned elsewhere in this paper and life cycle cost assessments.

PrimeShip-TLC (Total Lifetime Ship Care)

A schematic diagram of PrimeShip-TLC service for LNG carriers is shown in Fig. 5.

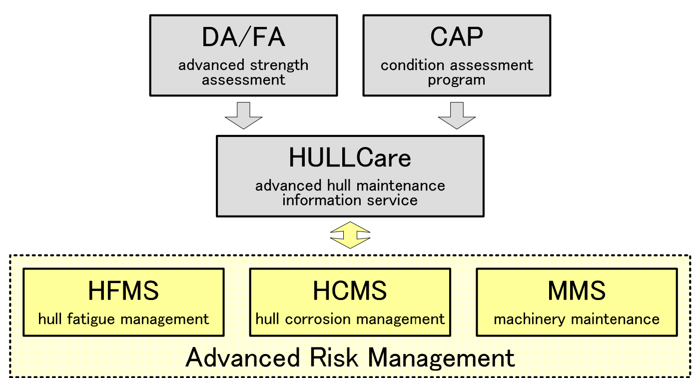


Fig. 5 PrimeShip TLC for LNG carriers

PrimeShip-TLC will encompass a total, comprehensive approach to ship care that integrates the current technical services that ClassNK offers such as DA/FA, CAP, HullCare, etc. noted above, with an innovative Advanced Risk Management (ARM) service.

PrimeShip-DA/FA is a technical service which provides latest advanced strength assessment tool based on the "Guidelines for Direct Strength Analysis" (ClassNK 2001a), the "Guidelines for Fatigue Strength Assessment" (ClassNK 2001b) and the "Guidelines for Ultimate Hull Girder Strength" (ClassNK 2001c). Here, reasonable and practical values of corrosion addition for each structural member are established according to the analyses of plate thickness measurements data of more than a million points by probabilistic corrosion model (Yamamoto 1998) which evaluates the process from the generation to progress of corrosion, statistically, as shown in Fig. 6.

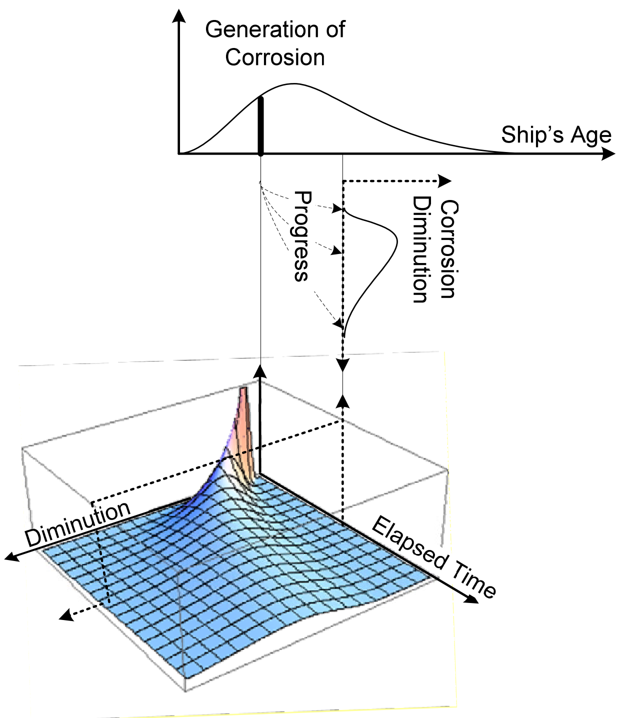


Fig. 6 Probabilistic corrosion model for evaluation of corrosion diminution

PrimeShip-CAP (Condition Assessment Programme) is a survey and inspection service used to assess and certify the condition of the hull structures, machinery equipment, and cargo systems of a ship based on the results of a detailed close up survey, strength evaluation, and fatigue assessment.

PrimeShip-TLA is a technical service used to assess the residual life of a ship currently in service. Here, an assessment of the fatigue integrity of the hull is performed taking into account the actual service experience of the ship to date. The repair, maintenance and reinforcement plan are examined based on the results of detailed condition assessment by the application of PrimeShip-CAP.

PrimeShip-HULLCare is an information service that provides class survey data, readily accessible via the internet. This service is based on a database that contains information on class service status, photos showing actual tank condition, thickness measurement data, repair plans and related specifications, coating maintenance records, and similar types of information essential to the good maintenance of the vessel.

Advanced Risk Management (ARM)

The Advanced Risk Management approach is based on highly reliable estimates of residual life that are made by feeding the knowledge and the results of actual condition monitoring of the state of deterioration of the hull structures back to the risk analysis process. The risk management system also includes the innovative application of enhanced construction monitoring techniques to confirm and ensure that the quality of construction is kept at a high level.

The flow of the basic concept of this life estimation procedure is shown in Fig. 7. It is anticipated that the age related condition of a ship will be different from initial design projections due to differences between the design conditions and the actual operating conditions encountered by the ship after it enters service. Therefore, it is essential that information from actual condition monitoring be fed back for proper risk analysis to be performed. This feedback makes it possible to more fully comprehend the current state of hull integrity and to predict with much greater precision the future transitions in condition that are most likely to take place.

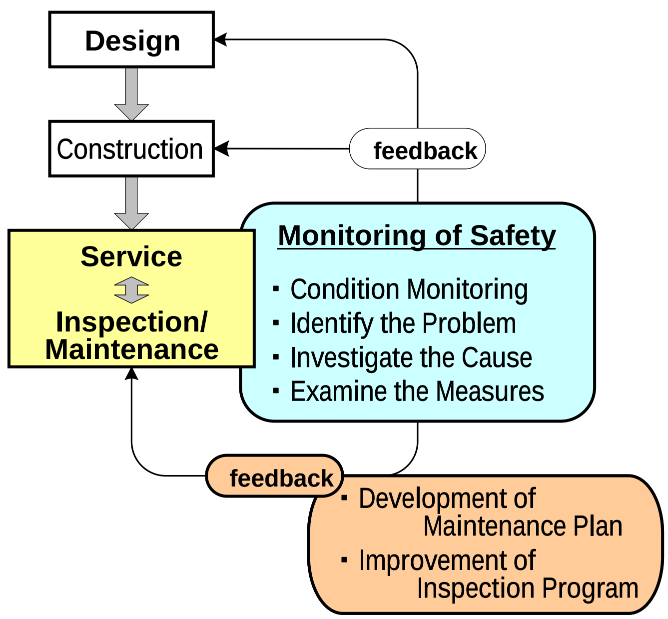


Fig. 7 Advanced Risk Management by Continuous Condition Monitoring

Consequently, an optimal maintenance plan based on a thorough understanding of the present condition of the hull structures combined with rational, highly accurate predictions of projected future deterioration can be established. Suitable measures to maintain the integrity of the ship to the expected levels of safety can then be appropriately put in place within the scope of the long-term maintenance and service plan.

The advanced risk management incorporates the following elements (see Fig.5):

(a) Hull Fatigue Management System (HFMS) for measuring and managing the fatigue strength of hull structures
(b) Hull Corrosion Management System (HCMS) for assessing and managing the corrosion of hull structures including the maintenance of coatings and determining the strength of corroded structures
(c) Machinery Management System (MMS) for managing the preventive maintenance of machinery and equipment through the application of in-service condition monitoring and a risk-matrix based assessment approach.

Each technical element in the Advanced Risk Management service, viz. HFMS, HCMS, and MMS, will constitute a new class notation to supplement the existing PrimeShip notations.

Hull Fatigue Management System

One important aspect of risk management in LNG carriers is the accurate prediction of estimated fatigue life of structural members. A methodology using Fatigue Damage Sensors (FDS) for predicting fatigue life incorporating coefficients influenced by loading histories against constant amplitude loading and mean stress levels is introduced and is verified through a series of fatigue testing and numerical simulation.

Fatigue Risk Ranking

For effective fatigue strength management, the fatigue risk is to be ranked effectively based on the design specification of the potential risk parts where the fatigue crack might be initiated. Further, the method of management during construction survey can be differentiated according to the rank of fatigue risk. The quality of survey can be brought to a high level by providing adequate instruction of the fatigue risky location and member to the surveyors and selection of necessary condition monitoring location and member from the fatigue strength view point.

Since the fatigue assessment method in PrimeShip-FA gives a rational result which can explain the tendencies of actual experienced fatigue damages, such a risk ranking can be reasonably done. The risk ranking is done based on the evaluations of:

(1) Possibility of fatigue crack initiation,
(2) Consequence of crack propagation, and
(3) Possibility of crack detection.

An example of the fatigue risk ranking procedure is shown in Table 2.

Fatigue Condition Monitoring

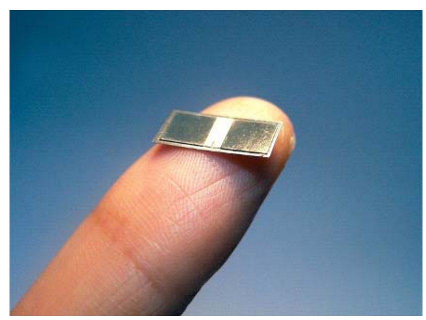
Fatigue deterioration condition cannot be confirmed until the initiated fatigue crack is detected. The risk of fatigue crack initiation becomes larger according to the fatigue damage accumulation due to the cyclic stress loaded in service. Therefore, it is necessary to assess the accumulated fatigue damage accurately in order to take measures for preventive maintenance such as appropriate reinforcement before crack initiation.

It is necessary to feed back information obtained by monitoring of fatigue condition to the analysis to presume the accumulated fatigue damage in service. Fatigue monitoring involves:

(1) Preparation of long-term wave scatter diagram of the experienced routes,
(2) Application of fatigue damage sensor (FDS), and
(3) Measurement of strain fluctuation.

A method of preparing long term wave scatter diagram of experienced routes has been used in PrimeShip-TLA. Fatigue strength is re-assessed according to the experienced long term stress range distribution.

Fatigue monitoring by applying FDS (Yamamoto 2007) is done by observing the length of propagated artificial crack initiated in the sensor shown in Fig. 8. The characteristics of crack propagation are independent of the crack length. Therefore, the crack length of FDS is proportional to the accumulated fatigue damage during the period of installation.



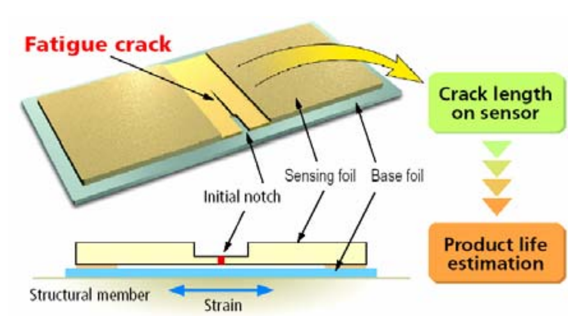


Fig. 8 Fatigue Damage Sensor (FDS)

Table 2 Example of fatigue risk ranking procedure

Item		Risk Score			Weight Factor
		3	2	1	
(1)	Possibility of Fatigue Crack Initiation	D > 0.75 Dcr	0.1Dcr < D < 0.75Dcr	D < 0.1Dcr	K1 = 2
(2)	Consequence of Crack Propagation	Functional Loss (leakage, collapse)	Possibility of Functional Loss	Large Redundancy	K2 = 1
(3)	Possibility of Crack Detection	Difficult	Moderate	Easy	K3 = 1
		Combination of Inspectability & Propagativity			
	Accessibility	Difficult unless scaffolding	Need Portable Ladder	Easy without Ladder	
	Environment	Bad (FOT, WBT with dark color paint, etc.)	Medium (WBT with light color paint, etc.)	Good (Exposed part, Dry space, etc.)	
	Inspectability	Bad	Medium	Good	
		Combination of Accessibility & Environment			
	Propagativity	Tensile mean stress field	Alternating mean stress field	Compressive mean stress field	
(4)	Total Risk Score	(1)*K1 + (2)*K2 + (3)*K7			
(5)	Risk Ranking	5 Rank Evaluation according to the Total Risk Score (**A**: 10%, **B**: 20%, **C**: 40%, **D**: 20%, **E**: 10%)			

Fatigue assessment procedure by FDS includes:

(1) Measure the crack length on the FDS,
(2) Estimate the accumulated damage to the FDS,
(3) Estimate the fatigue life of the FDS under the service load, and
(4) Estimate the fatigue life of the structure using S-N curves for FDS and structure.

A big advantage of fatigue assessment using the FDS is that the accumulated fatigue damage can be monitored by a visible scale like crack length. A ship structure is subjected to random wave loading, and the effect of mean stress due to the change of loading condition is large. The relation between the fatigue life of the FDS and the fatigue life of the structure under such a loading environment to put the fatigue monitoring by the FDS to practical use is investigated. A simple and compact device which measures strain fluctuation and counts hysteresis loop by strain flow method is developed for fatigue strength assessment.

Hull Corrosion Management System

Ballast tanks of ships are subject to corrosive environment and the internal members are protected by paint coating and supplementary sacrificial anodes. The effectiveness of paint coating is gradually deteriorated and the sacrificial anodes are gradually consumed as the paint coating is deteriorated.

The degree of coating deterioration is affected by various factors (ISSC 2006) such as the surface preparation before coating, kind of paint, coating procedure (number of layers, film thickness, etc.), conditions of use (frequency of ballasting, height of water, etc.), kind of adjoining tank etc. In addition, the degree of coating deterioration is affected by the maintenance history and procedure of coatings and sacrificial anodes. Therefore, the deteriorating condition of the paint coating in ballast tanks differs greatly in each ship, and it is also different in each tank of a ship.

Figure 9 shows the survey results of coating degradation of ballast water tank (Emi 1993) and typical coating conditions classified as “Good”, “Fair” and “Poor” (IACS 2006). IACS recommends that the coating condition should be maintained to at least “Fair” or more. In general, the area to be evaluated in a tank is wide and the tank environment is not good enough for survey by visual inspection. Therefore, the uncertainty in the judgment by the surveyor is a major concern.

It is important to evaluate the paint coating deterioration of the tank quantitatively, and to give the surveyor adequate information. For this reason, ClassNK have developed a paint coating deterioration sensor (PDS) and a quantitative assessment system of coating condition using the PDS.

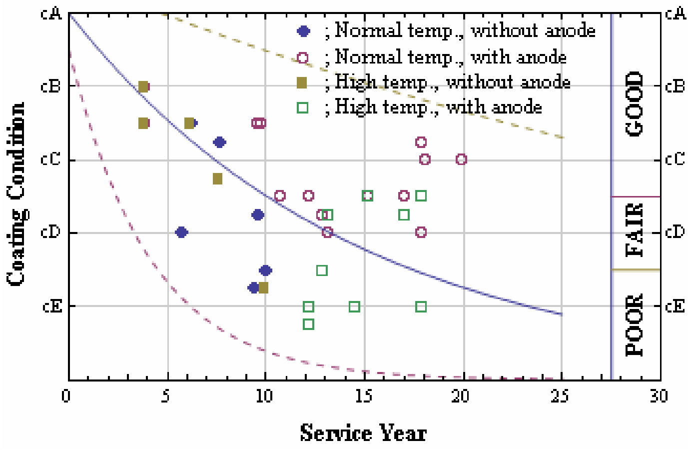
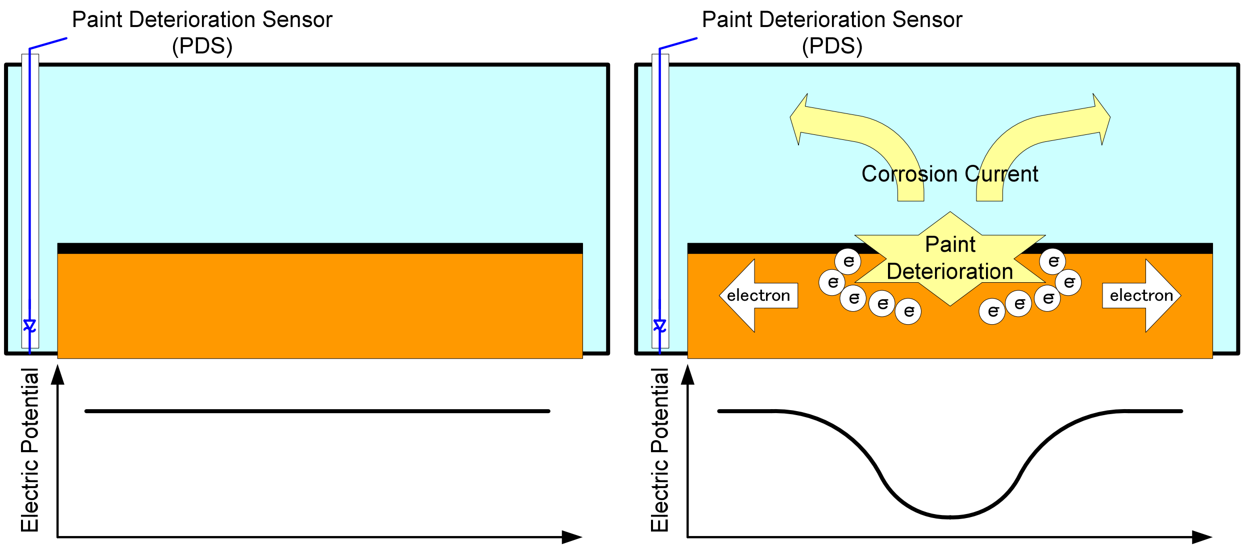


Fig. 9 Coating deterioration in ballast tanks

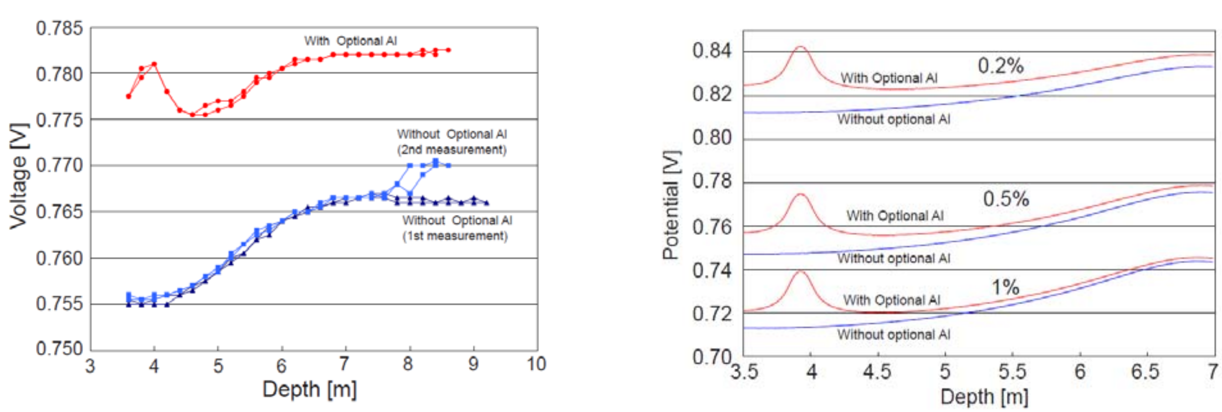
Figure 10 shows the concept behind the quantitative coating deterioration judgment system using the PDS. Since the ballast tank is paint coated and the supplementary sacrificial anode is attached, the corrosion current flows in the ballast tank between the deterioration part and the sacrificial anode through the ballast water when the paint coating is deteriorated. The system measures the change in the potential distribution in the tank using the sensor, and estimates average coating deterioration of the tank according to the inverse analysis of the result.

Figure 11 shows the potential measurements of a ballast tank of an LNG carrier of 23 years and the result of simulated potential distribution. Figure 11(a) shows the potential distribution in the side ballast tank measured in the direction of depth of the tank by PDS. On the other hand, Fig.11(b) is a result of the simulated potential distribution by the boundary element method which assumes the average coating deterioration in the tank.



(a) Intact coating condition (b) Deteriorated coating condition

Fig. 10 Schematic view of concept behind paint coating deterioration sensor (PDS).



(a) Measured (b) Simulated

Fig. 11 Potential distribution in the side ballast tank of an LNG carrier.

The simulation result obtained assuming an average paint coating deterioration of 0.5% shows relatively good agreement with the potential distribution measured by PDS, thereby confirming the effectiveness of the system.

Machinery Maintenance System

Conventionally, the inspection and maintenance of machinery and equipments are carried out at regular intervals. However, the need for ‘no overhaul’ inspection and condition monitoring has risen recently, mainly to avoid the possibility of mistakes while restoration and to do away with unnecessary overhauls.

By employing risk assessment, machinery management can be carried out reasonably and economically by giving priority to inspection of machinery and parts that have high risk. This concept is gaining widespread attention.

The risk is assessed by classification based on risk matrix which consists of likelihood and consequence of damage.

Integrated Information Management System

ClassNK is developing an Integrated Information Management System by integrating the results of the study presented in the paper with the extensive PrimeShip-HULLCare database that has data pertaining to a ship on the design, construction, inspection, and maintenance of the vessel. A schematic diagram of this system is shown in Fig. 12.

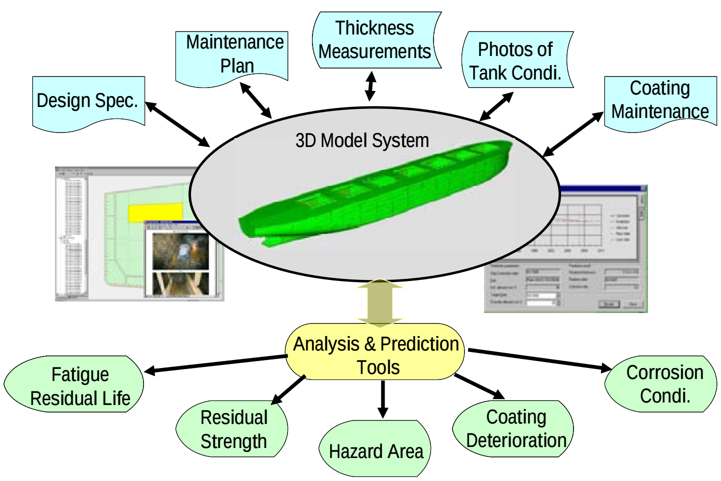


Fig. 12 Schematic of an Integrated Information Management System.

This comprehensive approach is expected to provide more effective support to the establishment of rational and optimum maintenance management plans based on a highly accurate assessment that reflects the actual condition of hull structures and machinery while also taking the design and actual operating conditions of the vessel into consideration.

CONCLUSION

In order to establish an organizational mechanism which would enable risk assessment of any area of the ship, ClassNK have initiated a research project to evaluate the application of various risk assessment methodologies in different areas such as the hull structures, propulsion systems, etc. of a ship. An outline of the project, some parts of which are still ongoing, are given in this paper.

This project effectively supports the development of an optimized maintenance plan based on risk assessment and life cycle cost assessment. This involves an accurate monitoring of the deteriorating condition, and a reliable assessment of residual life and strength, in addition to a refined inspection and survey scheme.

Risk analysis is carried out for both structure and machinery in accordance with prioritized accident scenarios in order to estimate the change in risk level of LNG carriers in the future, and change in risk level is estimated in conjunction with the identification of probable new risks that arise due to the changes.

Different propulsion plants are assessed based on the initial cost, economic efficiency, environmental impacts, reliability, redundancy of the components, maintainability, availability of fuels, securement of engineers, etc. Furthermore, to study the redundancy of BOG treatment equipment which is required according to IGC Code, risk assessment on several redundant systems is carried out.

ClassNK is currently developing a brand-new advanced ship maintenance support service program applicable to LNG carriers in line with the concept of PrimeShip, Total Lifetime Ship Care. This program aims at decreasing risk and life cycle cost of the ship, and supports the optimum maintenance of ship structures and machinery equipments against aging effect. This advanced ship maintenance support service will encompass a total, comprehensive approach to ship care that integrates several current technical services with an innovative Advanced Risk Management service for fatigue and corrosion of hull structure and for maintenance of machinery and equipment.

The information obtained from risk management described in the paper will then be integrated with extensive data contained in the PrimeShip-HULLCare database on the design, construction, and inspection maintenance of the vessel as the core of an Integrated Information Management System currently in the final stages of development.

Through this, it is expected that a more rational and strategic maintenance approach made possible by the advanced ship maintenance support service for LNG carriers will facilitate:

- Optimum hull structural maintenance planning based on the residual strength evaluation considering residual fatigue strength and actual corrosion conditions,

- Optimum coating maintenance planning based on predicted paint coating deterioration,
- Risk based optimum maintenance and overhaul of machinery and equipment, and
- Optimized inspections and close up surveys of hull structures as well as machinery and equipment.

ClassNK is confident that the implementation of the systems and services described above will contribute significantly to the further improvement of the safety and reliability of LNG carriers both now and in the future.

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