Proceedings of the 15th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2007
October 21-26, 2007, Miami, Florida, USA

NEW CONSTRUCTION OF "KAIEI-MARU" FOR THE TRANSPORT OF NUCLEAR FUEL MATERIALS

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ABSTRACT

The Nuclear Fuel Transport Co., Ltd. (NFT) has been safely transporting radioactive materials by 3 exclusive ships for LLW and SF transport. The oldest ship Hinoura Maru, however, retired in 2005 after 30 years of service and the NFT was required to build a replacement transport ship for the Japan Atomic Energy Agency (JAEA) Fugen SF after 2006.
The NFT ordered a new exclusive ship from the Mitsui Engineering & Shipbuilding Co., Ltd. and on September 7th, 2005, construction of the new ship began in the Tamano Works. On February 2nd of the following year, she was christened "Kaiei Maru" during the launching ceremony, and was completed on August 31st.

Kaiei Maru has the following features that make it distinct from conventional ships:
- Her safety equipment is updated and she is equipped with various devices for emergencies and physical protection.
- MCNP was used for as the shielding calculation code. This is the first time in Japan that MCNP codes were utilized for the licensing of radioactive material transportation. This utilization eventually led to the reduction of weight of shielding concrete by more than 100 tons when compared to DOT code calculation.
- Collision analysis was carried out by the FEM code to calculate the risk in the event of a collision between a VLCC and Kaiei Maru. The result of the analysis has proved that the loaded cask and the longitudinal bulkhead do not come into contact, even if a 15kt VLCC were to hit the center of her hull.

INTRODUCTION

The ship Hinoura Maru was decommissioned in December 2005 and the Japan Nuclear Cycle Development Institute (now the JAEA) requested us to construct a successor ship. The ship was planned to be used as a transport of spent nuclear fuel from the Fugen Nuclear Power Station to the Tokai Reprocessing Plant, and for other transport purposes. The specifications for the ship were framed with the view of using her also for the transport of spent nuclear fuel to the Rokkasho reprocessing plant and interim storage facilities.

BASIC PLAN

A case study was carried out taking the transport efficiency and construction cost into consideration, and a 4-cargo hold system was adopted for the new ship to enable the transport of various packages types of not only Fugen SF, but also the LWR SF to the Rokkasho reprocessing and interim storage facilities, category 1 materials, etc. The following concepts were adopted in the pre-design phase:

- Ship dimensions and navigational performance was settled to allow entry into all Japanese nuclear power plant ports.
- Propulsion system consisting of 2 sets of main engine and 2 sets of fixed pitch propeller was implemented to improve physical protection. This system can also be used for low speed navigation.
- A robust securing system was arranged under the deck to achieve a flat floor for the loading of many kinds of package.
- The “envelope spectrum” is used as the source spectrum, and it is used for shielding analysis. This assists with the calculation of typical package.
- An electric motor hydraulic system was adopted for the moving of the robust securing system, and to control the opening/closing of hatch covers and middle decks in order to improve loading reliability.

Taking the above into consideration, Kaiei Maru was designed not only in accordance with the Ship Safety Law and associated regulations, but also in accordance with special requirements for the transportation of nuclear fuel materials by ship, which are regulated by the “Regulation for the Carriage and Storage of Dangerous Goods”. The principal particulars of the ship are given in Table 1 as follows.

Table 1. Principal Particulars

Registered government	Japan
Classification	Nippon Kaiji Kyokai(NK)
Principal dimensions	
Overall length (L_{OA})	approx. 100m
Length p.p. (L_{PP})	approx. 95.0m
Breadth mld. (B_{MLD})	approx. 16.5m
Depth mld. (D_{MLD})	approx. 9.4m
Draft mld. (d)	approx. 5.4m
Deadweight	approx. 3,000 metric tons
Cargo loading capacity	12 packages (For SF package)
Main engine	
Type	2 cycle diesel engine (6 cylinders)
Model	Mitsui-MAN B&W x 2sets
Propeller	4 bladed fixed pitch propeller x 2 sets

Rudder	Schilling Rudder x 2 sets
Bow thruster	
Type	Controllable pitch type x 1 set
Thrust	10 metric tons
Electric power generator	
Main diesel generator	600kW x 2 sets
Aux. diesel generator	600kW x 1 set
Port use diesel generator	450kW x 1 set
Emergency diesel generator	95kW x 1 set

SPECIAL FEATURES

Safety Equipment

Kaiei Maru is provided with the following safety equipment in accordance with regulations. The regulations for the carriage of irradiated materials provide the following, which are classified into three large groups:

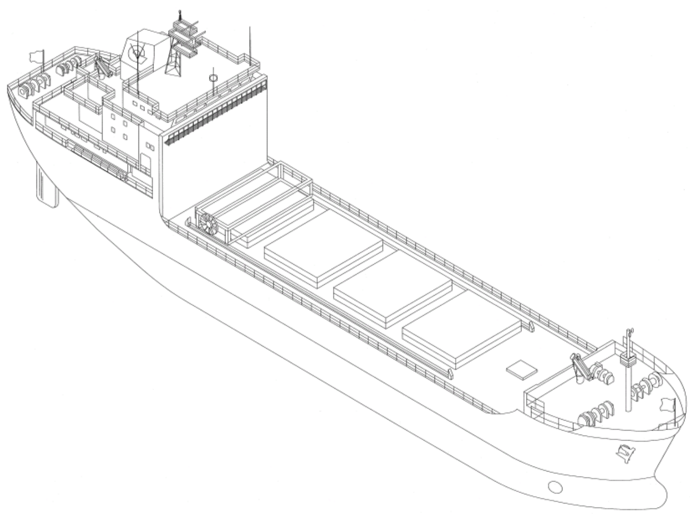

Figure 1. Kaiei Maru (bird's-eye view)

1. Requirements based on the INF Code of the SOLAS Convention:
   - Damage stability performance:
     satisfies the survival standard after assumed damage.
   - Double hull construction:
     ensures the safety of cargo by preventing the ship from sinking due to flooding of seawater in the event of collision or stranding.
   - Cask cooling system:
     keeps the ambient temperature around packages at 38 degrees C or less, and the surface of temperature of the packages at 85 degrees C or less
   - Cask securing system:
     prevents the casks from moving and overturning in the hold. This system can be operated by remote control.
   - Emergency water flooding system:
     floods the holds with water and can be operated from the bridge.
   - Alternative electric source:
     an emergency generator located on the bridge deck and an auxiliary generator located in the forward machinery room start automatically in case of main electric source failure.
   - Radiation monitoring system:
     monitors the radiation dose rate in each area and of the ship's personnel. It also monitors the surface temperature of each package and radioactive concentration of the bilge water, etc.

2. Requirements that Japanese government originally requires:
- Anti collision structure:
can absorb the collision energy of a T-2 tanker (deadweight: 23,400 tons, speed: 15kt) estimated by the Minorsky's method, without damaging the loaded package.

3. Requirements based on the IAEA recommendation "The Physical Protection of Nuclear Material and Nuclear Facilities":
- Physical protection equipment:
equipped with surveillance, invasion prevention, and special lighting devices. Also has ample communication equipment, allowing it to transport category 1 packages.
- Emergency plans:
prepared actions to counter any attempted unauthorized removal of nuclear material.

Moreover, important equipment and pipings are multiplexed, main engines and the electric power generators, etc. are made independent, and a securing system is equipped as an emergency plan.

MCNP Analysis

In designing the ship's shielding, conservative source conditions were required because various types of new packages currently being developed may be transported, including large transportable storage casks for interim storage. For instance, the dose equivalent rate at 1m from each package surface is assumed to be 100 micro Sv/h for both neutron and gamma-rays. Furthermore, for the source energy spectrum, the "envelope spectrum", which is the most conservative spectrum shown in the study of interim storage facility design in Japan, is used.

The design concept of the shielding structure and the shielding materials are the same as our another SF ship Rokuei Maru, which is nearly same size and has constructed about 10 years ago. Serpentine concrete, polyethylene, and major steel plates of the ship's structure are employed for shielding materials. The thickness of the serpentine concrete for the transverse bulkhead and wall is from 10-50cm and the thickness for the cross decks, hatch covers, and hatch coamings is 20cm. On the other hand, 9cm thick polyethylene blocks are placed on both longitudinal bulkheads in the holds and on the transverse bulkhead stem side of hold 1. The thickness of the steel plates is from 0.65-1.0cm. Consideration for the air and seawater around the ship were also based on the skyshine calculation.

The DOT3.5 code was used for the direct beam from the packages and MCNP code was used for the skyshine in Rokuei Maru. As the DOT3.5 is a two-dimensional discrete ordinates code, the evaluation of the parts such as the hatch cover shielding and the forward wall of the accommodation area, which the radiation penetrates obliquely, must be modeled quite conservatively. In designing Kaiei Maru, the continuous energy Monte Carlo code, MCNP, was used for evaluating the dose equivalent rates by the direct beam and skyshine simultaneously. Thus, the shielding structures of Kaiei Maru can be modeled exactly in the calculations even for the direct beam. As the source particles with the envelope spectrum need to be generated at the surface of each package, a subroutine is provided and added to for MCNP code. The major shielding calculation conditions are shown in Table 2.

Table 2 Major Shielding Calculation Conditions

Shielding Material	Serpentine Concrete: 2.17 g/cm^3(11 wt% H_2O) Polyethylene: 0.837 g/cm^3 Steel Plate: 7.8 g/cm^3
Code	MCNP4c + JENDL3.2 (for neutron) MCPLIB02 (for gamma)Estimator: Point tally
Source Condition	Radiation: neutron (100%) and gamma-ray (100%) Strength: 100 micro Sv/h at 1m from package surface Energy Spectrum: "envelope spectrum"(most conservative) Generating point: cask surface

Typical calculation results in the case of both neutron 100% and gamma ray 100% and the limits from the regulations are shown in Table 3. F.S.D. (Fractional Standard Deviation) from statistical error is shown in parentheses. The secondary gamma is also calculated in the case of neutron 100%.

All calculation results are sufficiently lower than the regulation limits.

Table 3 Calculation Results of dose rates

Position	Dose rate [micro Sv/h]*		Regulation Limit [micro Sv/h]
	Neutron 100%	Gamma 100%	
Bridge	0.47 (0.028)	0.27 (0.027)	1.8
Engine Room	0.32 (0.032)	0.29 (0.031)	
Forecastle deck	0.35 (0.021)	0.21 (0.031)	
AUX. machinery room	0.18 (0.032)	0.35 (0.034)	
External surface of conveyance	109 (0.011)	53 (0.015)	2000
2m from the external surface	21 (0.002)	18 (0.002)	100

*: values in the parentheses show F.S.D.

Although the total weight of concrete for shielding decreases about 100 tons from Rokuei Maru, the dose rates satisfy the requirements. It shows that this calculation method by using MCNP code is rational and applicable for the shielding calculation of direct beam and skyshine for such a large system.

FEM Analysis

In accordance with a special Japanese government's order, the hull structure of Kaiei Maru has been strengthened in case of collision. In the provision, the necessary condition is ruled using the simplified method. To estimate the safety of the packaging in more detail, we made optional calculations collision damage using the FEM in the scenario that a VLCC (L: 320, B: 58, D: 31 (m), 290,000DWT) were to run into the Kaiei Maru.

The FEM code used in the analysis was LS-DYNA. It is non-linear explicit FEM code and can take plastic material and large deformation into account. The element size was determined so that the proper failure modes could be simulated in the analysis. Dynamic response of both ships were calculated until maximum deformation was obtained. In the analysis model, a VLCC collided into the third cargo hold (midship) of Kaiei Maru at 90 degrees, though the possibility of a collision is extremely low. Estimates of four cases to determine the combined state of navigational and loading conditions were calculated as below:

Colliding ship: VLCC (Full load or Ballast / 15kt)
Collided ship: Kaiei Maru （Full load / 80% MCR or Stop）

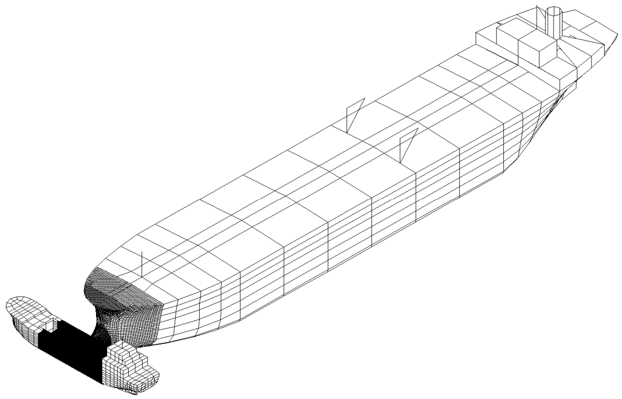

Figure 2. FEM Analysis Model

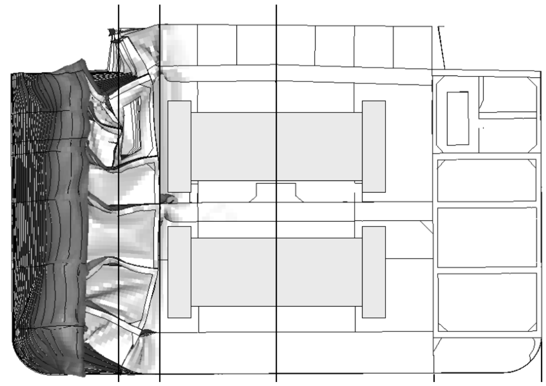

Figure 3. After the Collision

In each case, there were space between the deformed longitudinal bulkhead and package, so safety of the package was confirmed because of they were not in contact with each other. When in the situation that a VLCC were to collide into the cargo hold in an area other than midship, its results showed that it would less a severe due to the energy conversion into the rotational moment.

CONCLUSIONS

We used the MCNP and FEM calculations for design and applied equipment for physical protection to an exclusive ship for the first time, and were able to obtain a lot of findings. Furthermore, the results from the MCNP shielding design could also be utilized for the authorization of the equipment and facilities of the transport package, and we could convince of that Kaiei Maru , she had been strengthened according to the simplified method, had very strong anti collision structure from the result of the FEM.

The construction of Kaiei Maru was completed on August 31st, 2006, and she safely completed her first transportation on October 20th, 2006. She will contribute to the establishment of the nuclear fuel cycle by continuing Hinoura Maru's task of safe transport by using the latest software and hardware available, and fulfill the needs of stakeholders.

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