On-Board Experiment and Monte Carlo Analysis of Dose-Equivalent Rate Distribution in the LLW Shipping Vessel "Seiei Maru"

K. Ueki, A. Ohashi
Ship Research Institute

T. Sasao, T. Sanui, T. Fuse
Nuclear Fuel Transport Co., Ltd.

INTRODUCTION

On-board experiments were carried out in a LLW (low level radioactive wastes) shipping vessel, the Seiei Maru, in which 2,880 LLW drums were loaded by 360 containers in six holds, and gamma-ray dose-equivalent rates were measured mainly on the hatch covers of the holds and also in the accommodation area. Furthermore, the gamma-ray doses were measured to estimate the contribution of the sky-shine on the quay when the Seiei Maru entered Mutsu Ogawara port.

The continuous energy Monte Carlo code MCNP 4A (Briesmeister, 1993) was employed to analyze the measured gamma-ray dose-equivalent rates on the hatch covers of the holds. In order to give the gamma-ray source strength at every container in which 8 LLW drums were housed, 60 containers in a hold were modeled at every container in the present Monte Carlo analysis. This detailed model is called the "heterogeneous model" in this study. The homogeneous model in which 60 containers were homogenized through the hold of the LLW source region, was also taken up to compare the result with the heterogeneous model in the Monte Carlo analysis. The gamma-ray source strength was uniformly distributed in the homogenized region. The homogeneous model can be employed in the point kernel code QAD-CG (Hopkins, 1977), the one-dimensional transport code ANISN (Engle, et al., 1967), and the two-dimensional code DOT 3.5 (Rhodes, et al., 1973). However, the heterogeneous model is difficult to calculate exactly except by the Monte Carlo method. In the QAD-CG code, the source geometry is able to model as precisely as the MCNP 4A, but the QAD-CG cannot give the source strength and energy spectrum at every container like the MCNP 4A.

ON-BOARD EXPERIMENT IN THE SEIEI MARU

Outline of the Seiei Maru

The LLW shipping vessel Seiei Maru has following outlines.

Construction	:	Sept. 1991
Total length	:	100 m
Width	:	16 m
Depth	:	8 m

Deadweight	:	3,000 tons
Service Speed	:	13 knots
Holds	:	7 holds
LLW Containers	:	Total 384 containers, in which 8 LLW drums are housed (No. 2, No. 3・・・・No. 7 holds load 60 containers, No. 1 hold loads 24).

The LLW ship has been plying between each nuclear power station and Mutsu Ogawara port where the nuclear-fuel-cycle facilities are located. The on-board experiment was carried out to measure the gamma-ray dose-equivalent rates in and out of the ship in Dec. 1993.

On-Board Experiment

The gamma-ray dose-equivalent rates were measured mainly on the hatch covers of the holds, in the accommodation area of the ship, and also on the quay in Mutsu Ogawara port when the Seiei Maru entered there. The measured dose points on the center line of the Seiei Maru are shown in Fig. 1, and the corresponding measured dose equivalent rates are summarized in Table 1. In Table 1, the values at the dose point 7 to 30 are the maximum ones on each measured line. There are 5 measured points from the port side to the starboard on the measured line. The dose point 31 is located under the No. 3 hold hatch cover and the dose was measured when the hatch cover was opened in Mutsu Ogawara port, so that the measured value was much higher than the other points. In all the measurements, the scintillation survey meter of a ALOKA was employed. In accordance with the manual, the survey meter has a measurement error of $\pm 15\%$ in the measured values. Accordingly, the measurement error is indicated in tables and figures.

In Table 1, the maximum dose point on the hatch cover is at No. 17 of No. 5 hold, and the corresponding dose-equivalent rate is 1.17 μ Sv/h. The maximum dose equivalent rate on the hatch cover of the No. 3 hold is 1.00 μ Sv/h at No. 23 point, and the dose on the back side of the hatch cover is 19.7 μ Sv/h at No. 31. The dose attenuation ratio of 1/20 (1.0 μ Sv/h / 19.7 μ Sv/h) is due to the shielding effect of the hatch cover, which is constructed with 1 cm-thick steel + 16 cm-thick concrete +1 cm-thick steel. The maximum dose point in the accommodation area is at No. 1 on the wheel house deck, and the corresponding value is 0.05 μ Sv/h. The controlled dose-equivalent rate in the accommodation area is 1.8 μ Sv/h in the Japanese sea-transport regulation. Accordingly, the magnitude of 0.05 μ Sv/h is 1/36 of the regulation.

The measured dose equivalent rates were between 0.04 and 0.06 μ Sv/h at 50m-distance from the side surface of the Seiei Maru in Mutsu Ogawara port, and those measured values were not affected by the hatch cover opening or closing. Accordingly, the contribution of the sky-shine could not be cleared by the measurement, so it was estimated by the Monte Carlo calculation. The net dose-equivalent rates were between 0.01 and 0.03 μ Sv/h at the dose point.

Each container houses 8 LLW drums, of which are made of concrete. The most of the gamma-ray sources in a LLW drum are ^{60}Co and ^{137}Cs. There is a small source of ^{58}Co in the LLW. However, the magnitude of the ^{58}Co is 10% of the ^{60}Co at the most, and half-life is 70.8 days. The LLW drums transported by the present shipment are more than 5 years passed since the LLW were solidified by concrete. Accordingly, the gamma-ray sources were recognized to be ^{60}Co and ^{137}Cs at shipment. The magnitude of the gamma-ray sources is indicated in Table 2. There was no container in the No. 1 hold in the present shipment.

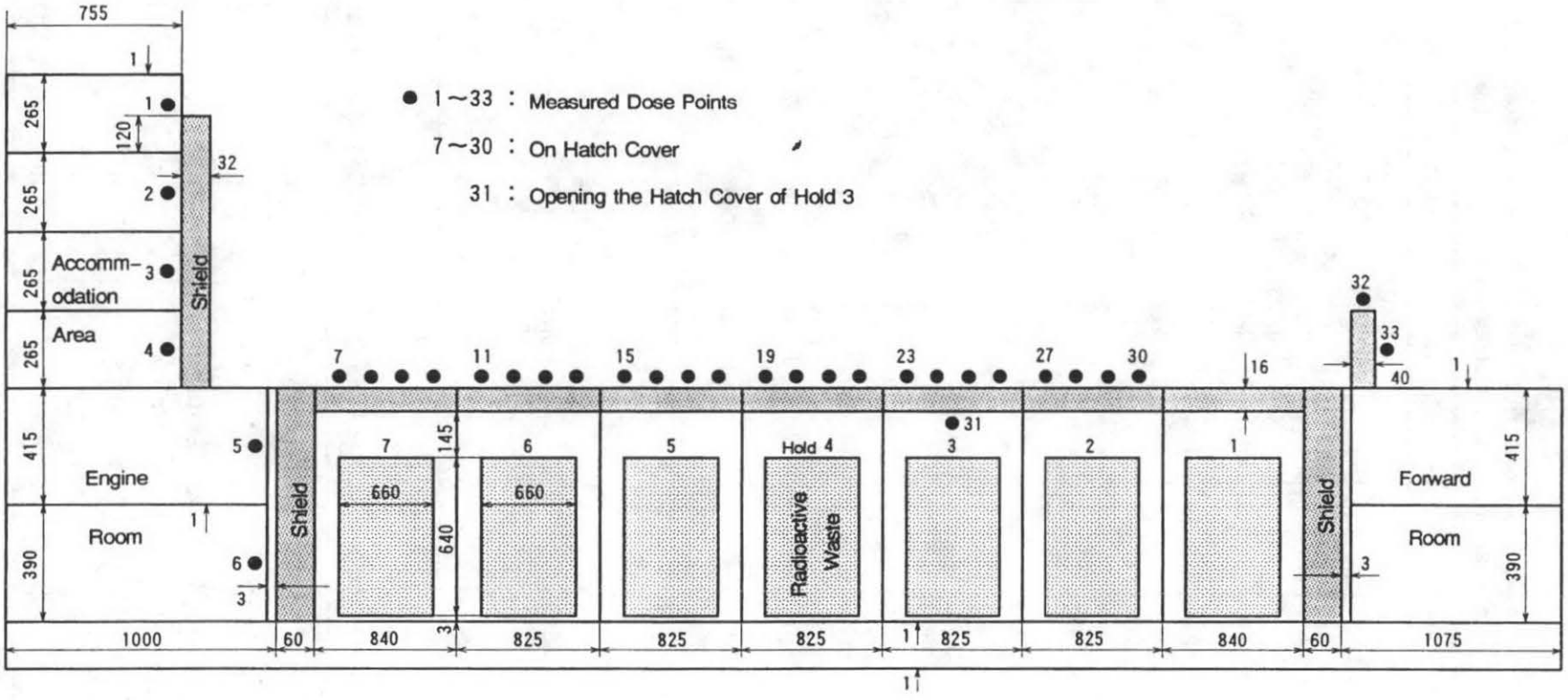

Fig.1. Calculational model of a LLW vessel (Unit : cm)
(Vertical)

Table 1 Measured dose-equivalent rates. The values at dose point 7 to 30 are the maximum ones on each measured line.

Dose Point	Measured Dose-Equivalent Rates (μSv/h)
1	0.05 ± 0.0075
2	0.045 ± 0.00675
3	0.045 ± 0.00675
4	0.025 ± 0.00375
5	0.025 ± 0.00375
6	0.02 ± 0.003
7	0.50 ± 0.075
8	0.82 ± 0.123
9	0.77 ± 0.1155
10	0.63 ± 0.0945
11	0.59 ± 0.0885
12	1.09 ± 0.1635
13	0.81 ± 0.1215
14	0.58 ± 0.087
15	0.58 ± 0.087
16	1.10 ± 0.165
17	1.17 ± 0.1755
18	0.92 ± 0.138
19	0.63 ± 0.0945
20	0.96 ± 0.144
21	0.78 ± 0.117
22	0.66 ± 0.099
23	0.40 ± 0.06
24	0.57 ± 0.085
25	1.00 ± 0.15
26	0.91 ± 0.1365
27	0.39 ± 0.0585
28	0.58 ± 0.087
29	0.83 ± 0.1245
30	0.75 ± 0.1125
31	19.7 ± 2.955
32	0.04 ± 0.006
33	0.01 ± 0.0015

Table 2 Total gamma-ray source strength (^{137}Cs and ^{60}Co) of LLW in a hold.

Hold	^{137}Cs (photons/s)	^{60}Co (photons/s)
No. 2	9.62×10^{10}	4.2×10^{10}
3	8.29×10^{10}	4.2×10^{10}
4	7.82×10^{10}	4.1×10^{10}
5	5.30×10^{10}	4.6×10^{10}
6	2.74×10^{10}	6.2×10^{10}
7	2.22×10^{10}	4.4×10^{10}

MONTE CARLO ANALYSIS OF EXPERIMENTS

Modeling of Source Term and Structures in Vessel

In order to bring out the best of the Monte Carlo method, as illustrated in Fig. 2, the 8 LLW drums in a container were divided into two blocks, i. e., each block has 4 drums. Consequently, gamma-ray source intensity, and energy spectrum of the LLW could be given in each block. This detailed model is called the heterogeneous model in this paper. The homogenized model of the LLW storage hold was also analyzed by the Monte Carlo method to compare the result with the heterogeneous model. The homogenized model can be calculated by the point kernel code QAD, the one-dimensional code ANISN, and the two-dimensional code DOT.

The homogenized and the heterogeneous models are summarized as follows.

(1) Homogenized Model

(i) The gamma-ray sources in a hold are distributed in a homogenized region of $660 \times 880 \times 640^{h}$ cm.

(ii) Even though concrete density of the solidified LLW is 2.2 g/cm^3, concrete of the LLW, steel of the LLW drum and the container, air in and around the container are homogenized. Then the density of the homogenized region is reduced to 0.612 g/cm^3.

(2) Heterogeneous Model

(i) Each container consists of two blocks of $270 \times 51 \times 89^{h}$ cm, each block has homogenized the 4 LLW drums, and the density is 1.69 g/cm^3. In the present calculation, the source condition of the two blocks is the same.

(ii) The dimension of each container is $320 \times 176 \times 107^{h}$ cm, and it is covered with 0.16 cm^{t} of steel. The heterogeneous model of a hold loads the 60 containers in it. The air in and around the container is not homogenized. Accordingly, the gamma-ray streaming through the air is taken into account in the Monte Carlo analysis.

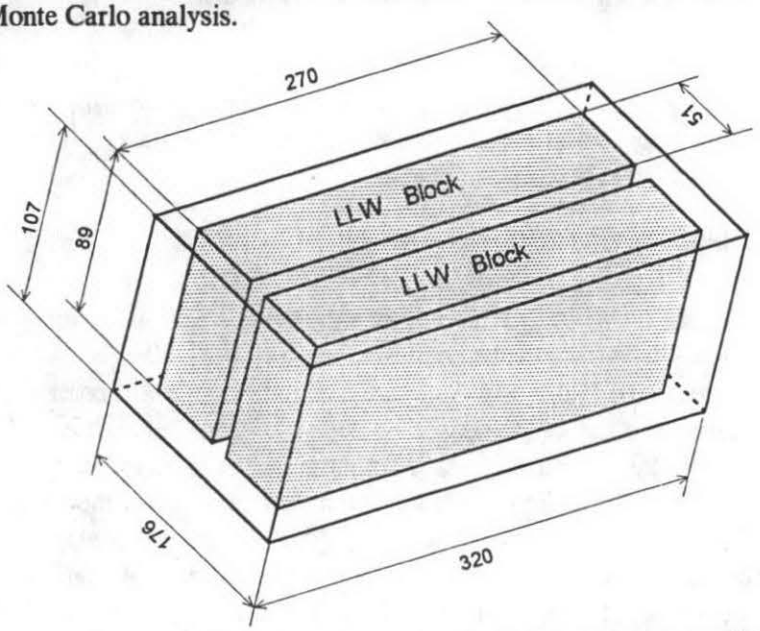

Fig.2. A LLW container model used in the heterogeneous model of LLW region in a hold. Dimensions are all centimetres.

Comparison and Discussion of Experiment and Monte Carlo Analysis

As described before, the measurements of the dose-equivalent rates were carried out mainly on the hatch covers. Accordingly, Monte Carlo calculations were concentrated upon the hatch covers. Figure 3 shows the comparison of the gamma-ray dose-equivalent rates between the measurements and the Monte Carlo calculations on the hatch cover of the No. 4 hold. The fsd's (fractional standard deviation) of all the calculations were within 10 %, and the calculation time in each model, i. e., the heterogeneous model and the homogenized model, was set in 500 min. by the HP 755 workstation.

As compared with the experiment, the Monte Carlo results are overestimated at all the dose points in Fig. 3. The Monte Carlo results with the heterogeneous model are overestimated by a factor of 1.5 to 2.5 and by a factor of 2.25 to 7.5 with the homogenized model. However, the calculated profiles of the dose equivalent rate distributions are almost the same as the experiment. The reasons of the overestimation are as follows :

(1) In the homogenized model, the gamma-ray source region of the LLW was homogenized over the 60 containers with air in and around them. Then the density of the source region is 0.612 g/cm^3. On the other hand, the minimum unit of the heterogeneous model, the block in which the 4 LLW drums are homogenized, and the geometry of the 60 containers in which the two blocks are loaded in each container and air in and around the containers are taken into the calculations without being homogenized. Then the density of a block is 1.69 g/cm^3. Consequently, even though the gamma-ray streaming through the air gap in and around the containers, due to the difference of the density in the source region, the Monte Carlo results with the homogenized model are to produce more large dose-equivalent rates than that of the heterogeneous model.

(2) The gamma-ray sources are distributed uniformly in the source region. Accordingly, some of the sources are generated from nearer locations than that of the real source ones and also than that of the heterogeneous model. As a result, the homogenized model also leads to more large doses than that of both the measurements and the heterogeneous model.

(3) The data on the gamma-ray source strength and radioisotopes of the LLW drums are offered by the nuclear power plant, and the data are also utilized to the safety assessment of the LLW disposal. Therefore, some safety margin was to be taken into the source data. Accordingly, the Monte Carlo results were overestimated the measurements.

Contribution of Sky-Shine

The dose equivalent rates were measured when the hatch cover was opening and closing at 50 m-distance from the side surface of the Seiei Maru on the quay. The natural back ground subtracted doses were between 0.01 and 0.03 μ Sv/h in which the gamma-rays coming from the LLW source, the ship structures, and the sky-shine were included. Accordingly, it is difficult to take out the net contribution of the sky-shine from the present measured data, so that the contribution of it was estimated from the Monte Carlo calculations with the homogenized model of the LLW source region. In the first calculation, air was considered up to 1,500 m around the ship, and it was up to 50 m around the ship in the second calculation. In the Monte Carlo calculations, the hatch cover of the Seiei Maru was opened. The result of the first calculation was 5.24×10^{-2} (fsd : 0.035) μ Sv/h and the second was 4.64×10^{-2} (fsd : 0.036) μ Sv/h at the detector point. The calculated dose-equivalent rate of 5.24×10^{-2} μ Sv/h is overestimated by a factor of 1.7 to 5.2 as compared with the

measured values, and the contribution of the sky-shine is estimated to be approximately 11 % of the total dose at the measured point. The tendency of the overestimation in the Monte Carlo results is the same as the results on the hatch cover.

CONCLUSIONS

The following remarks were obtained as compared with the on board experiments and the Monte Carlo analysis.

1. The Monte Carlo analysis with the heterogeneous model of the LLW source region could produce good agreement as compared with the measured dose-equivalent rates on the hatch cover. On the other hand, the Monte Carlo analysis with the homogenized model overestimated the measured values by a factor of more than 5.

2. Estimating from the present study, the dose-equivalent rate on the hatch cover is to be less than 2.5 μ Sv/h at the maximum dose point, whereas the regulation limit is 2000 μ Sv/h. Accordingly, the safety factor (regulation limit/ measured or calculated value) is more than 800. On the shielding point of view, it is confirmed that the shielding design of the Seiei Maru is safe enough. The maximum dose equivalent rate at 50-m distance from the ship on the quay is no more than 0.05 μ Sv/h. This value corresponds to 0.438 mSv/y. Accordingly, radiation exposure to the public is also safe enough on the ship.

3. The contribution of the gamma-ray sky-shine was obtained with and without air around the detector located on the quay at the port by the Monte Carlo calculation. In consequence, the contribution of the sky-shine was estimated to be approximately 11% to the dose equivalent rate under opening of a hatch cover in the ship.

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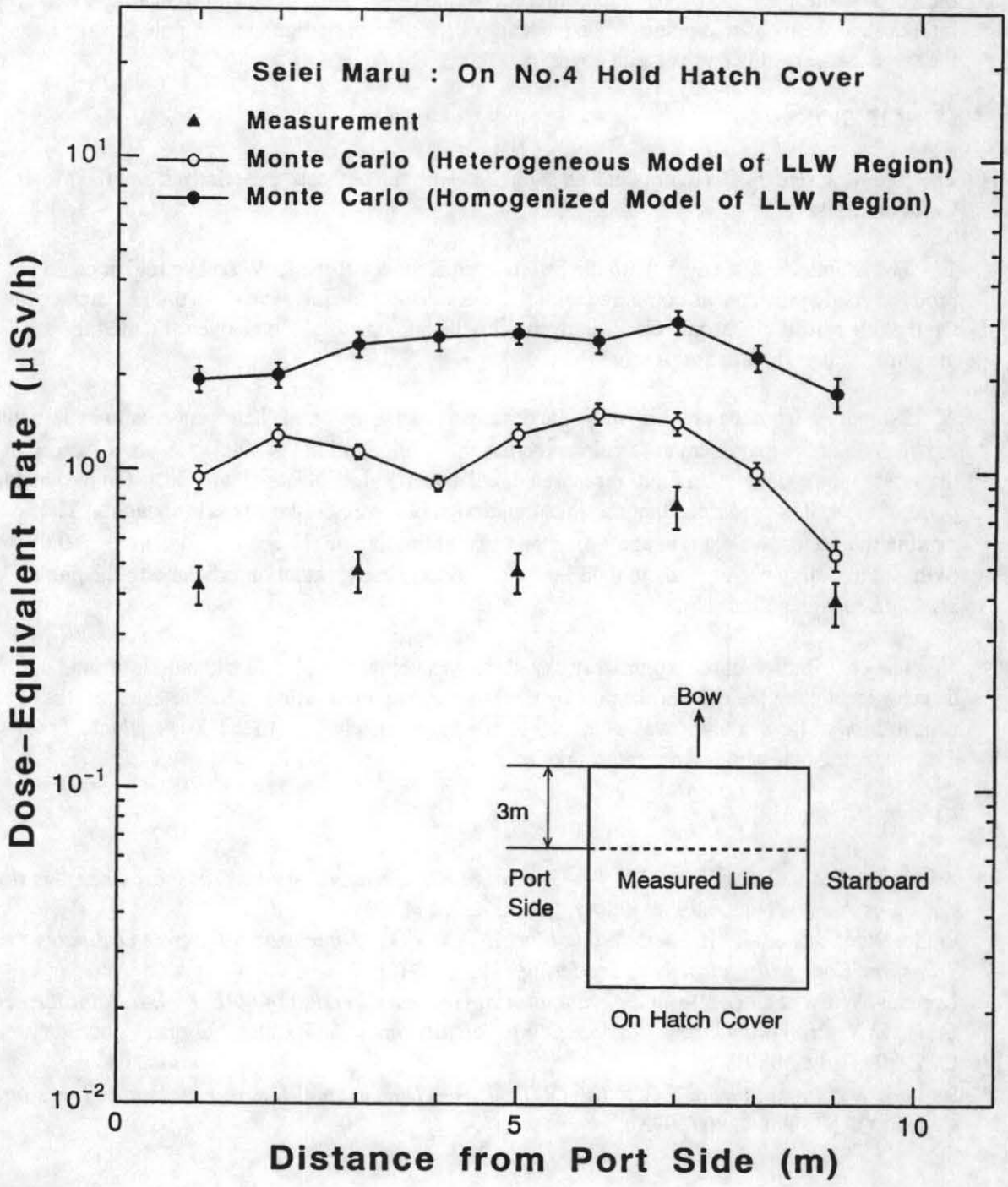

Fig.3. Comparison of gamma-ray dose-equivalent rates between measurements and Monte Carlo calculations on No.4 hold hatch cover of the Seiei Maru.
Measured points are at 3 m-distance from the bow side.