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TECHNICAL DATA

Reactivity Accident of Nuclear Submarine near Vladivostok

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After the collapse of the Soviet Union and consequently the termination of the Cold War and the disarmament agreements, many nuclear warheads are in a queue for dismantling. As a result, substantial number of nuclear submarines equipped with ballistic missiles will be also withdrawn from service. However, Russian nuclear submarines have suffered from reactivity accidents five times. In the paper, a reactivity accident on a nuclear submarine that happened at Chazhma Bay located between Vladivostok and Nakhodka on August 10, 1985, has been described. In addition, the characteristics of submarine nuclear reactors, procedures of refueling, and the possibility of a similar accident are given. Further, the radiological risk to Japan and neighboring countries has been assessed by using an atmospheric pollutant transport code, WSPEEDI, developed by Japan Atomic Energy Research Institute. The radiological risk has been evaluated for the Chazhma Bay accident and for a hypothetical reactivity accident of a retired submarine during defueling, assuming winter meteorological conditions. The analyses have shown that the radioactive material might be transported in the atmosphere to Japan in one to several days and might contaminate wide areas of Japan. Under the assumptions taken in the paper, however, the radiological dose to population in the area might be not significant.

KEYWORDS: ***nuclear submarines, reactor accidents, reactivity accident, pollutants, atmospheric transport, Vladivostok, Russia, radioactive contamination, WSPEEDI, Chazhma Bay, analysis***

I. Introduction

In Russia, Vladivostok and Murmansk are important military ports for Russian Pacific and Northern Fleets respectively. These are the homeports of Russian nuclear submarines for maintenance and refueling of nuclear reactors. From 1957 to January 1998, 248 nuclear submarines were built in Russia as listed in **Table 1**[(1)]. As a result of START-II (Strategic Arms Reduction Talks II) treaty, substantial number of nuclear submarines will be withdrawn from service. Information on numbers of submarines in service and retired are not available. However, it is considered that the Russian Pacific Fleet has about 40 nuclear submarines in service and more than 60 retired submarines that are in a queue for decommissioning[(2)-(6)]. The Russian submarines are usually equipped with two identical nuclear reactors. Therefore, it can be said that there are more than 100 nuclear reactors which may be decommissioned at the Zvezda military shipyard, at Bolshoi Kamen near Vladivostok, located about 700 to 1,000 km from the Japanese coastal area.

After the collapse of the Soviet Union, a lot of secret information was declassified and released. Especially, radioactive contamination in Russia, caused by nuclear arms race and nuclear fleet operations was compiled and published, *i.e.*, so called, 'White Book'[(7)], by the Russian government. The 'White Book' revealed that radioactive wastes were dumped into the Sea of Japan by Russian Pacific Fleet for many years. That prompted the Japanese government to finance ($25 million) for the building of a liquid radioactive waste processing facility at the Vladivostok area. Among this declassified information, there were found five reactivity accidents[(8)], listed in **Table 2**, and frequent Loss-of-Coolant Accidents (LOCA) aboard nuclear submarines. Severodvinsk and Chazhma Bay are shipyards for nuclear submarine maintenance and refueling for Northern and Pacific fleets respectively. Nizhny Novgorod is a shipyard for building nuclear submarines.

In the Russian Far East, there were one reactivity ac-

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Table 1 Russian nuclear submarines as of January 1998[1]

Type of submarine	Total built	In service	Retired
SSBN	91	27	63
SSGN	60	12	48
SSN	92	34	55
Other	5	4	1
Total	248	77	167

SSBN: Nuclear Ballistic Missile Submarines
SSGN: Nuclear Cruise Missile Submarines
SSN: Nuclear Fleet Submarines (usually attack submarines)
'Retired' does not include submarines sunk at sea, used as training ships or converted from one type to another.

cident and two LOCAs. The two LOCAs did not release radioactive material to the environment but the reactivity accident, referred to as the Chazhma Bay accident, was considered to be the most hazardous accident. It was a reactivity accident releasing about 2.6×10^{17} Bq[9] of radioactive material to environment and killing 10 officers on board by a steam explosion. The region where the accident occurred on August 10, 1985 near Vladivostok, one year before the Chernobyl, was completely under military control and remained a secret for many years.

The Chazhma Bay accident was happened during the regular refueling process. The refueling is still essential for existing nuclear submarines in service and is supposed to be performed at military shipyards, such as Zvezda, near Vladivostok. Further, the retired submarines need to be defuelled. The defuelling is considered to be a similar process to the refueling. Therefore, the possibility of a reactivity accident during refueling and defuelling cannot be completely denied.

In the paper, extensive literature survey is conducted to reveal reactivity accidents of Russian nuclear submarines. Many pieces of information are collected from various sources, such as newspapers, internet web sites, scientific reports and papers in English and in Russian as well. Chapter II of the paper is mainly based on such efforts where the pieces of the collected information are reorganized to show what are Russian nuclear submarines, especially reactors, and what happened at Chazhma Bay. In Chap. III, analysis is performed to evaluate radiological risks of reactivity accidents to neighboring countries.

II. Chazhma Bay Accident

The Chazhma Bay accident was a reactivity accident followed by the steam explosion. In this chapter, the Chazhma Bay accident is described together with characteristics of submarine nuclear reactors, procedures of refueling, and the possibility of a similar accident.

1. Nuclear Reactors of Russian Submarines

More than ten different types of nuclear submarines have been constructed in Russia since 1957 but most of the nuclear reactors on-board can be classified into three PWR types and one liquid-metal (Pb–Bi) cooled type (LMR)[10], as shown in **Table 3**.

As seen in **Figs. 1** and **2**[11], one submarine is usually equipped with two identical PWR type reactors of 70 to 90 MW(t) each or with one PWR type reactor of 190 MW(t) in order to generate steam in the secondary loop, to be fed to turbines for submarine propulsion. The fuel enrichment is about 20% and sometimes includes up to 45% in order for flattening of power distribution.

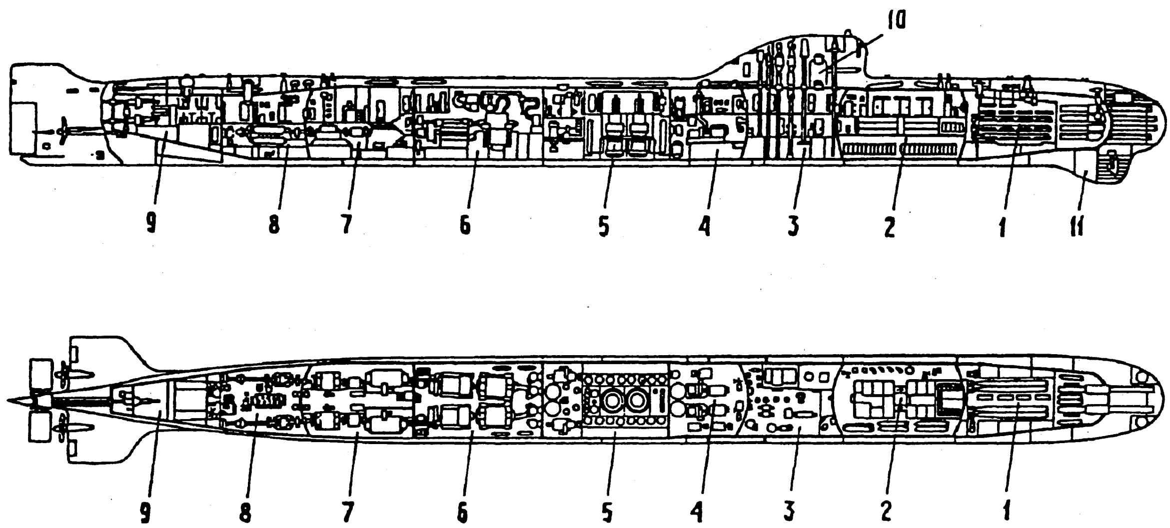
For the basic reactor physics analysis, it is essential to have the data on dimensions, arrangements and nuclide compositions of fuel and control rods. However, such data are still classified. It is supposed, in the case of PWR type core, that the fuel is U–Al alloy of 10 mm in diameter with Zr–Nb alloy or stainless steel cladding, which is arranged in a triangular lattice. The size of the active core is not known but a reactor pressure vessel is supposed to be cylindrical and made of carbon steel, with 1.4 to 2.0 m in diameter and 3.4 to 5.0 m in length, containing 248 to 252 fuel assemblies. Data on control rods is completely absent. However, it is assumed in some of the literature that there are three scram rods, and nine control and shim rods, made of borated carbon steel 10 mm in diameter[12].

Table 2 Reactivity accident of Russian nuclear submarines[8]

Year	Place	Reactor status	Cause of accident	Radionuclide release	Casualty
1965	Severodvinsk	Refuelling	Carelessness of crew (detail unavailable)	Yes	(Information unavailable)
1968	Severodvinsk	Maintenance	Rod withdrawal due to wrong cable connection	None	None
1970	Nizhny Novgorod	Under construction	Unfixed rod pushed up by strong coolant flow	Yes	(Information unavailable)
1980	Severodvinsk	Maintenance	Rod withdrawal due to disconnected safety system	Small	(Information unavailable)
1985	Chazhma Bay	Refueling	Rod withdrawal due to lift up of upper lid	Substantial	10, Many received high dose.

Table 3 Reactor characteristics of Russian submarines[8][13][22][32]

Reactor type	Number of reactors built	Reactor power (MW(t))	Fuel enrichment (%)	Total ^{235}U (kg)
PWR-1	110	70	20	50
PWR-2	267	75–90	21	70
PWR-3	52	190	21–45	115
LMR (Pb–Bi)	9	73–155	90	—



1: Torpedo compartment, 2: Battery compartment, 3: Central control room, 4: Diesel compartment, 5: Reactor compartment, 6: Turbine compartment, 7: Electronic motors compartment, 8: Support equipment compartment, 9: Stern compartment, 10: Conning tower, 11: Sonar

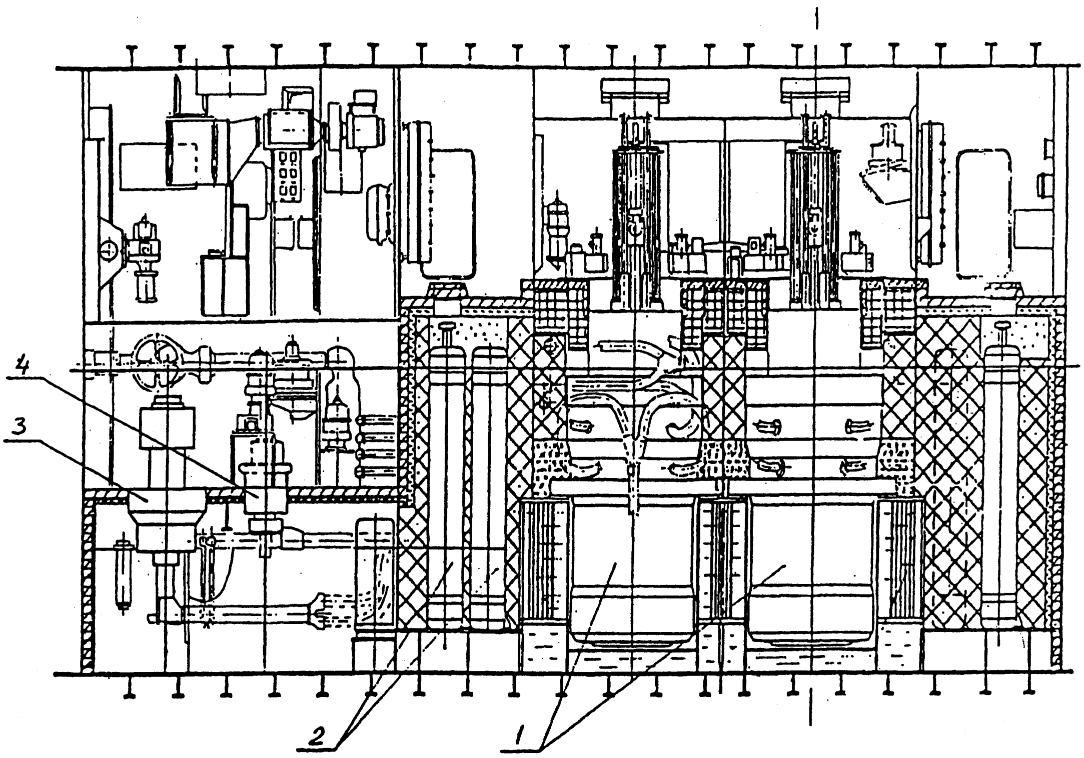
Fig. 1 Schematic view of first Russian nuclear submarine, Project 627/Leninsky Komsomol (November Class) [11]

All of spent fuel assemblies of a submarine nuclear reactor are replaced by new ones after 7 to 10 yr of service, during a regularly scheduled overhaul. The fuel burn-up at EOL (End of Life) is also not known. However, it is deduced as 7 to 10 GWd/core from the data of dumped nuclear submarine reactors near Novaja Zemlya[13] which shows that the average burn-up per year is roughly 1 GWd/core.

2. Refueling Procedure of Submarine Reactors

The refueling process consists of unloading spent fuel assemblies followed by loading fresh fuel assemblies. The unloading of spent fuel from submarine reactors is considered as a potentially dangerous work. The refueling requires the removal of upper lid of the reactor pressure vessel. Since the upper lid is equipped with all the control rods, some measure must be taken to keep the core sub-critical without control rods. Even at the EOL core, the excess reactivity is estimated to be 3.5 to 5.0% Δk[14]. One such measure is to drain all the water from the core to keep it sub-critical. However, decay heat removal from the spent fuel may become a problem. Further, the radiation level will increase after draining water and the radiation protection of workers has to be considered. There is no information on the cooling time after the reactor shutdown, before starting the refueling operation. The refueling process may be described as follows[11][15]:

(1) A special suction tube is inserted into the hole of the upper rid designated for positioning the scram rod.
(2) All water is drained from the primary loop and the absence of water is verified.
(3) The crane of refueling service ship, as shown in **Photo. 1**[16], removes the upper lid.
(4) The refueling machine with fuel transfer container is positioned above the core.
(5) The spent fuel assembly is removed from the core by the refueling machine and stored in the fuel transfer container.
(6) After filling all of seven compartments by spent fuel assemblies, the fuel transfer container is craned back to the refueling service ship.
(7) Fresh fuel assemblies are loaded to the fuel transfer container after unloading the spent fuel assemblies to the storage space in the refueling service ship.



1: Nuclear reactor, 2: Pressurizer, 3: Main pump, 4: Service pump

Fig. 2 Schematic view of reactor compartment [11]

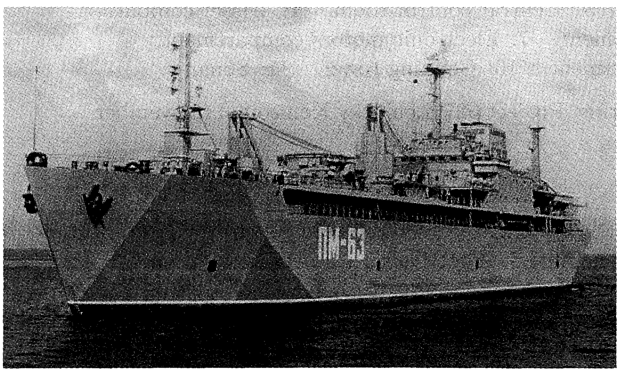


Photo. 1 Refueling service ship [16]

(8) The fresh fuel assemblies are loaded in the core. Then, the process is repeated from step (5) until the core is fully loaded with fresh fuel assemblies.
(9) After removing the refueling machine, the upper lid with control rods is placed to close the core.
(10) The coolant water is filled to the primary loop. The leak tightness of the upper lid seal is verified.

Specially trained and certified personnel under the strict regulations carry out all of the above processes.

The Chazhma Bay accident was happened at the step (10) of the refueling process. Workers found that the seal of the upper lid was incomplete and decided to crane up the upper lid slightly to fix the problem. The decision was made without any consultation of supervisor and violated the regulations. Further, it should be noted that there is no special place for refueling but on the sea, as shown in **Photo. 2**[17]. It is easily imaginable that the position of craned up object is quite unstable due to rocking of a submarine and/or a refueling service ship by possible waves and wakes.

3. Chazhma Bay Accident

The Chazhma Bay is used as a base of Russian Pacific Fleet, located almost in the middle of Vladivostok and Nakhodka as seen in **Photo. 3**[18]. The Chazhma Bay accident was a reactivity accident, happened at 10:55 local time on August 10, 1985, nine months before the Chernobyl Accident.

The refueling of the both of PWR-1 type reactors onboard for the Echo-II type nuclear submarine was completed the day before. However, the workers found leaks from the seal of the upper lid. The chief of workers decided to fix it without reporting the leak and they lifted up the upper lid but they did not drain the water of the primary loop, neither did they detach the lattice, which was used to keep control rods in place. When the upper lid was raised for a few centimeters, a navy torpedo boat swept by, that created a big wake. The wake rocked the refueling service ship and its long crane arm resulting in rapid withdrawal of all control rods. The rapid reactivity insertion caused a huge power pulse followed by steam explosion[19].

Due to the explosion, the 12 t upper lid and all of fuel assemblies were blown out from the reactor compartment and the submarine pressure hull was destroyed. The ra-

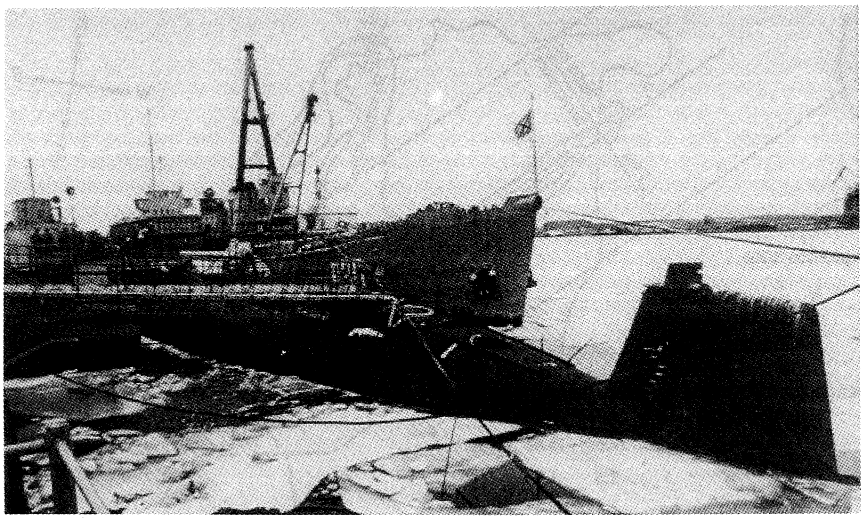


Photo. 2 Submarine and refueling service ship with crane [17]

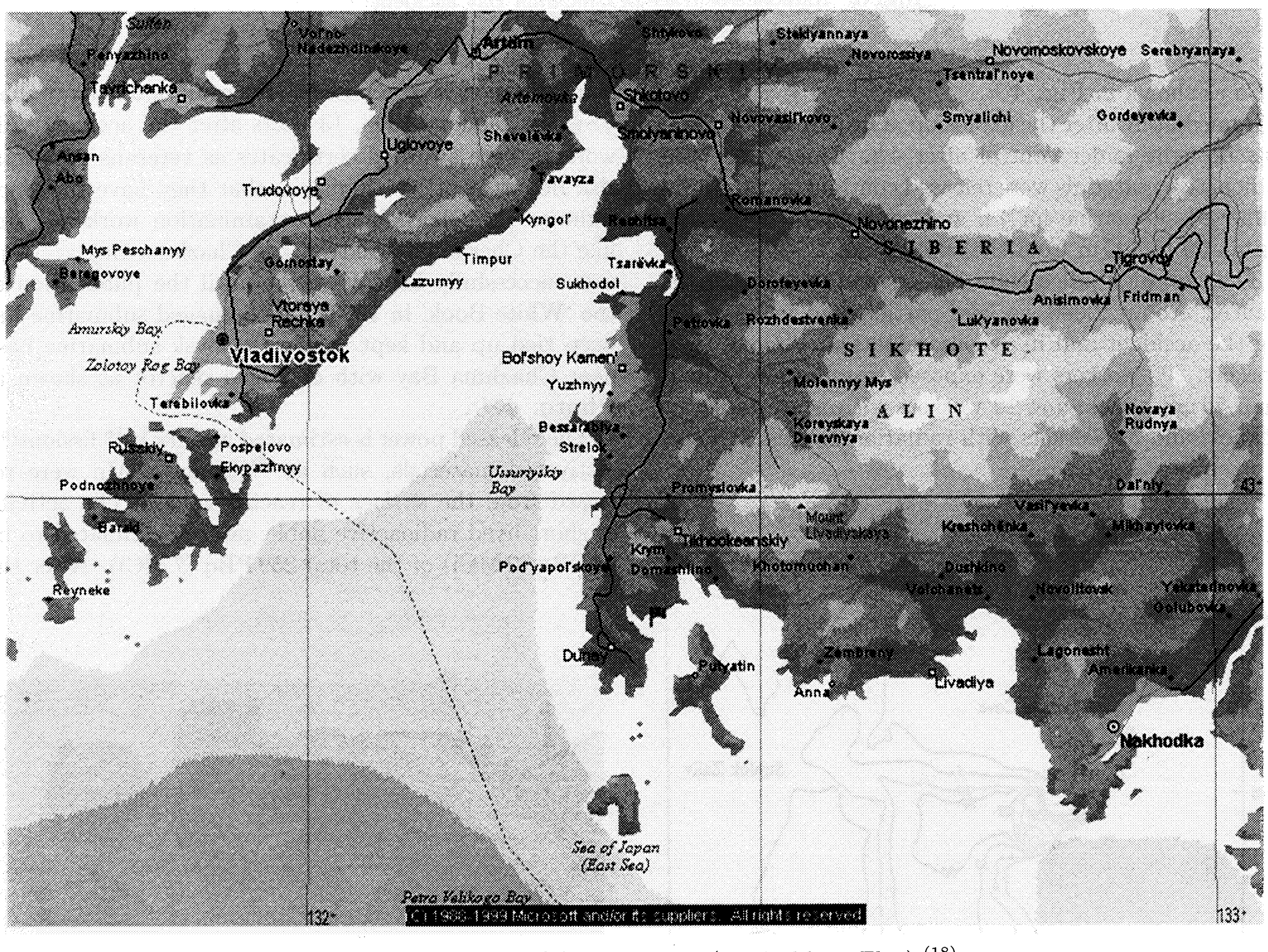


Photo. 3 Location of Chazhma Bay (Marked by a Flag) [18]

dioactive plume was observed just after the explosion and was 20 to 30 m in size at about 50 m above the submarine. The plume was then moved to northwest direction, however, most of the radioactive materials were trapped by the thick forest located on the slope of nearby hills. Since it was in the late morning of a summer day, the sea breeze was blowing from the sea to the mountains. The plume created a radioactive trace of 3.5 km long and 200 to 650 m wide as shown in **Fig. 3**. Further, the bottom of the Chazhma Bay was also contaminated mainly by

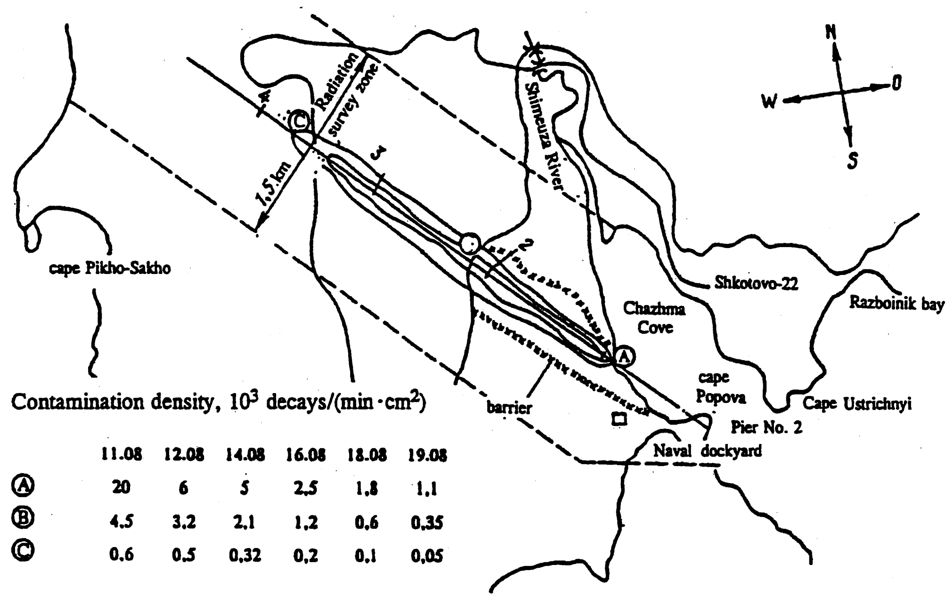


Fig. 3 Radioactive trace of Chazhma Bay accident(9)

^{60}Co as shown in **Fig. 4**(9).

Immediately after the explosion, a fire broke out which was brought under control after 4 h. Due to the fire, radioactive materials were released continuously from the damaged submarine for 7 h and contaminated the area within 50 to 100 m from the submarine.

The explosion killed eight officers and two workers instantly. About 2,000 workers participated in terminating the accident and in decontamination. Among these workers, 290 workers were exposed to radiation of more than 50 mSv, including 10 workers with acute radiation sickness and 39 workers with radiation reactions. Especially, firemen were exposed to the radiation of more than 6 Sv. In January 1998, 13 years after the accident, 205 workers were awarded certificates as veterans of special risk department(20). It means that they have the same right as the Chernobyl decontamination workers. Unlike the Chernobyl accident, the Chazhma Bay accident was successfully kept as secret until the publication of the 'White Book' in 1993. The damaged submarine has been tied up and kept at the Pavlovsk submarine base near Chazhma Bay with damaged reactor as shown in **Photo. 4**(21).

The released power is estimated as 5.0×10^{18} fissions(9). Activated materials, such as ^{60}Co and ^{54}Mn were released from the surface of reactor vessel. The activity of short-lived radioactive noble gases is estimated to be 74 PBq (2 MCi) of the total 259 PBq (7 MCi). After the

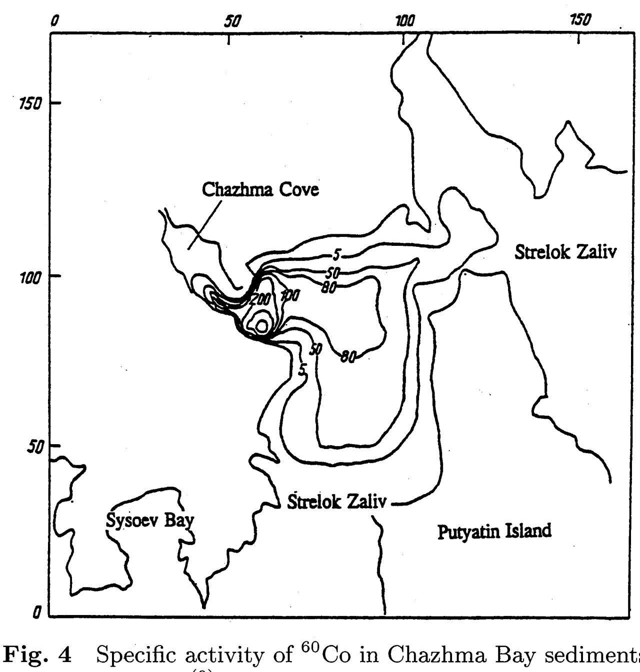


Fig. 4 Specific activity of ^{60}Co in Chazhma Bay sediments (Bq/kg) (9)

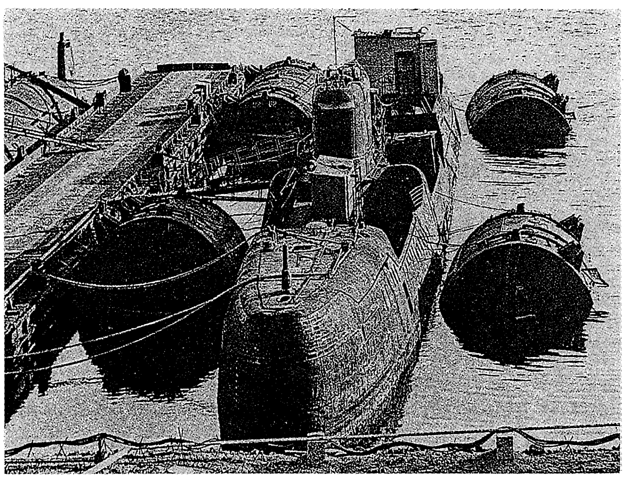


Photo. 4 Damaged submarine by Chazhma Bay accident (21)

explosion, the fire broke out. However, the fire might not have generated substantial radioactive aerosols since there remained little radioactive materials in the reactor. As the core was loaded with fresh fuel, hazardous radioactive nuclides, such as ^{137}Cs, ^{134}Cs and ^{90}Sr, were negligible from the viewpoint of radioecology. After the decay of radioactive nuclides with short half-lives, the radioactive iodine was considered to be the major cause of radiological dose.

4. Risk Estimation of Reactivity Accident during Refueling

As shown in Table 2 of Chap. I, there were two reactivity accidents during refueling by the year of 1985. By using **Fig. 5**(2), it is possible to estimate the number of refuelings performed up to 1985. It is known that refueling is carried out after 7–10 yr of operation during a regularly scheduled overhaul. Assuming each submarine experiences refueling twice every 7 yr, it is possible to estimate roughly from the figure that about 270 submarines were refueled by the year 1985. Each submarine has two identical reactors, therefore, it can be said that there were two reactivity accidents among 540 reactor refuelings. Then, the frequency of reactivity accidents during refueling would become roughly 0.37% per refueling. In the case of longer refueling cycle, the frequency will increase since the number of refueling decreases. By the same reason, the existence of retired submarines will also make the frequency slightly higher.

As described in Chap. I, there are about 40 nuclear submarines in service and over 60 retired submarines at Russian Far East. When we assume that all of these 100 submarines will experience refueling or defueling in 10 yr, there will be 200 times of reactor refueling/defueling processes. Assuming the frequencies of reactivity accidents during refueling and defueling are the same, the expected number of reactivity accidents will become roughly 0.74 time in 10 yr. Recently, submarines have been refueled every 3 to 5 yr(22). In this case, the expected number will increase.

The above estimation is very simple and the value might include large ambiguity. After experiencing such accidents, some countermeasures might be taken to prevent the occurrence of the similar sequences and, in this case, the frequency might be reduced, however, such information is not available.

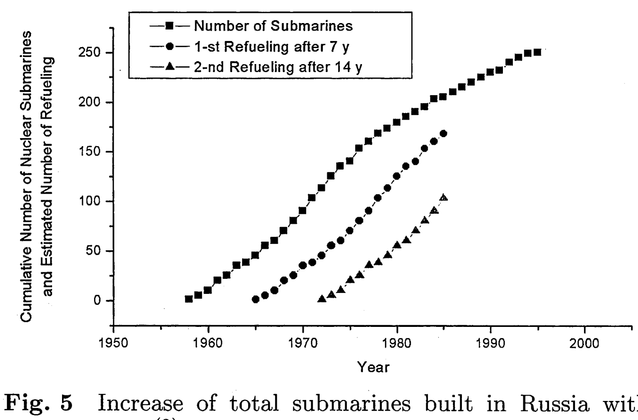


Fig. 5 Increase of total submarines built in Russia with Year (2) (Estimation of rufueling number by 1985)

III. Atmospheric Transport Analysis

The reactivity accident, such as Chazhma Bay accident, usually releases radionuclides into the atmosphere and consequently, contaminates large area. In general, between Japan and Russian Far East, the wind directions are the south to the southeast in summer and the northwest in winter. This might be the main reason why the radionuclides released by the Chazhma Bay accident occurred in summer were not observed in Japan(23)(24). Assuming the winter wind condition, the atmospheric transport of radionuclides has been analyzed by employing the WSPEEDI code(25)-(27), a Worldwide version of SPEEDI (System for Prediction of Environmental Emergency Dose Information), developed by JAERI (Japan Atomic Energy Research Institute), in order to assess the radioecological consequences of a reactivity accident near Vladivostok to the neighboring countries, especially to Japan. The atmospheric transport of radionuclides has been analyzed for two reactivity accidents, *i.e.*, the Chazhma Bay accident and a hypothetical reactivity accident during unloading spent fuel from retired nuclear submarines. In this chapter, after describing the WSPEEDI code briefly, the source term of two reactivity accidents is discussed followed by the analysis results by the WSPEEDI code of three different wind conditions in winter.

1. WSPEEDI Code

The WSPEEDI code was developed by JAERI in order to forecast contamination and radiological dose caused by nuclear accidents. The WSPEEDI code is designed to simulate the long-range transport of radionuclides and is able to model up to the scale of a hemisphere. The vertical dimension of the computational domain is 10 km which roughly corresponds to the top of troposphere.

The WSPEEDI code consists of a mass-consistent wind model to generate large-scale wind field and a particle random walk model to analyze atmospheric dispersion and deposition of radionuclides, and radiological dose. The models are able to simulate complicated source geometry, three-dimensional topography, and spatial heterogeneity and time dependency of the wind field.

The mass-consistent wind model predicts three-dimensional wind fields from worldwide meteorological observation data or global meteorological forecast data obtained from a meteorological agency, such as ECMWF (European Center for Medium-range Weather Forecast). The model is a diagnostic type and the temporal resolution of prediction depends on time interval of available data, typically 6 hours. It is essential to employ the mass-consistent wind model in order to avoid a significant mass imbalance foreseen in the process of mapping the observed meteorological data onto three-dimensional girds of the model when the observed meteorological data is employed as input data.

In the particle random walk model, the atmospheric dispersion of radionuclides is analyzed by tracking a large number of marker particles as radionuclides that are discharged from the source and moving downwind. In addition to the movement following the wind field resolved by the model grid system, each particle moves randomly in horizontal and vertical directions to simulate diffusion by atmospheric turbulence. The model assumes that the height of the atmospheric boundary layer (ABL) is 500 m. The performance of these two models and the assumption of the ABL height were verified by comparing predicted results and measured data obtained by 2,000 km-scale field tracer experiments, ETEX (European Tracer Experiment)(28)(29). The comparison showed that the WSPEEDI code predicted within factors of 2 and 5 for 35 and 58% among all of concentration data measured at 168 different locations respectively. The model equations and numerical procedures can be found elsewhere(26)(27)(29)(30).

2. Source Term of Reactivity Accident

As discussed in Sec. II-3, the Chazhma Bay accident released radioactivity of 259 PBq. However, due to the fact that the core was loaded with fresh fuel and consequently there was no buildup of fission products, it was considered that most of the radionuclides generated by the accident had short half-lives and disintegrated very quickly. For a long-range atmospheric transport, it is necessary to focus on a radionuclide which is enough quantity from the viewpoint of dispersion and whose half-life is long enough to travel across the Sea of Japan since it takes from one to several days to reach Japan from Vladivostok. Assuming the radioactivity of 259 PBq was a result of accidental nuclear fissions and applying the Hunter-Ballow's law, *i.e.*,

$$A(t) = A_0 t^{-1.2},$$

where $A(t)$: Radioactivity at t minutes after fissions,
A_0: Radioactivity by fissions at t=0,
t: Time after fissions in minutes,

the radioactivity after 24 h would become only 43 TBq (1.2 kCi). In addition to the reduction of the radioactivity by the time factor, the spatial dilution of nuclide concentration is also expected in the course of atmospheric transport. In the paper, as a source term for the atmospheric transport analysis, radioactive iodine is employed for the analysis since it has rather high fission yield and sufficiently long half life. By using fission yield of iodine and total number of fissions (5.0×10^{18}), estimated radioactivities of ^{131}I, ^{133}I and ^{135}I are 145 GBq, 3.10 TBq and 9.20 TBq respectively. Applying 0.2 as a release factor of iodine to the atmosphere taken from the NATO (North Atlantic Treaty Organization) study(31), the released radioactivities used in the atmospheric analysis are shown in **Table 4**. In order to study the spatial dilution effect, ^{137}Cs is used in the analysis as a pseudo-stable nuclide because of the sufficiently long half-life (30.0 yr) for the time duration of days.

Table 4 Radionuclide released to atmosphere for analysis of Chazhma Bay accident

Nuclide	Half-life	Activity (GBq)
^{131}I	8.04 d	29
^{133}I	20.8 h	620
^{135}I	6.61 h	1,840

Table 5 Radionuclide released to atmosphere for analysis of hypothetical reactivity accident

Nuclide	Half-life (yr)	Activity (GBq)
^{137}Cs	30.0	350,000
^{134}Cs	2.06	35,000
^{90}Sr	28.8	70,000

The hypothetical reactivity accident during refueling of submarines in service and defueling of retired submarines was studied by NATO. The NATO study includes the atmospheric transport analysis around the city of Murmansk, where navy bases of the Russian Northern Fleet are located but the study in relation to the Russian Pacific Fleet is absent. However, the submarines in service and retired are in almost the same situation, such as the same submarine and reactor types, similar fuel burn-up and similar duration of service and standby for decommissioning, both at Pacific and Northern Fleets. Therefore, the source term data used for the atmospheric transport analysis in NATO study can be used for the present analysis. In the hypothetical reactivity accident, different from the Chazhma Bay accident, the reactor is supposed to be filled with spent fuel and the accumulated fission products are the main radionuclides for the atmospheric transport analysis. The amount of radioactivity and radionuclides used in NATO study as shown in **Table 5**, are also used in the paper(31).

In the NATO study, the fission product inventory was calculated assuming the reactor operation at 67.5 MW for 1.25 yr followed by 5 yr of cooling after the reactor shutdown. Further, the estimated excursion power was 2,500 MWs (8×10^{19} fissions) that is supposed to be enough to melt fuel cladding and consequently steam explosion.

3. Atmospheric Transport of Radionuclides from Vladivostok in Winter

By using the WSPEEDI code, two types of reactivity accidents, the Chazhma Bay and the hypothetical accidents, are analyzed for the radioactive contamination by atmospheric transport of radionuclides. These accidents are assumed to occur at a navy base near Vladivostok (43.1°N, 131.9°E) in winter. For winter meteorological condition, the wind fields of January 1997 analyzed by a routine numerical model of Japan Meteorological Agency are employed. The wind field data are given as a grid dataset with temporal resolution of 6 h. The horizontal spatial resolution is 2.5°×2.5° of longitude and latitude. The vertical data points are surface and at the standard pressure levels (1,000, 850, 700, 500, 400, 300, 250, 200, 150 and 100 hPa). In the paper, no precipitation is assumed. The calculation domain is a 2,500 km square, with the Sea of Japan at the center. The domain is divided into 50×50×20 (vertical) grid cells, and hence, each grid cell becomes a 50 km square horizontally. The vertical grid is variable with height and the highest in air density is at the surface layer from 0 to 50 m above the ground.

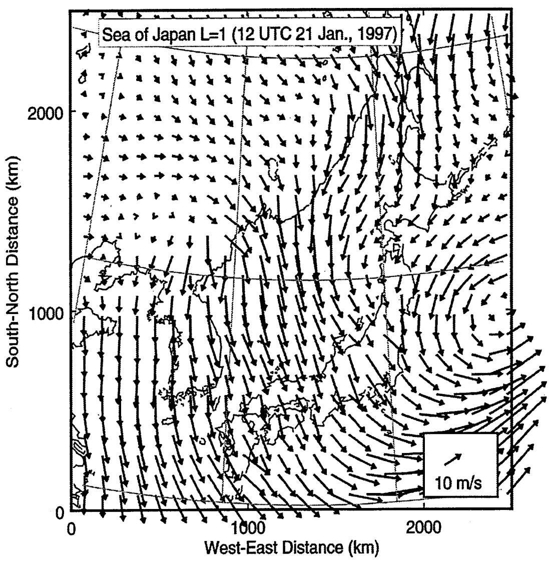
(1) Patterns of Wind Field

At Vladivostok, the wind direction was generally north in January 1997, up to the height of several hundred meters. However, we have selected three types of wind patterns for analysis as shown in **Fig. 6**. The figure shows the wind patters at the height of 100 m above the ground. The wind patterns shown in Figs. 6(a) and (b) are similar but wind speed in Fig. 6(a) is about three times higher than that of Fig. 6(b). In Fig. 6(c), the wind blows toward the Korean Peninsula and then to the Japanese Islands. Here, we denote the wind patterns of Figs. 6(a), (b) and (c) as "Strong North Wind (SNW)", "Weak North Wind (WNW)" and "Cyclonic Wind (CW)" respectively.

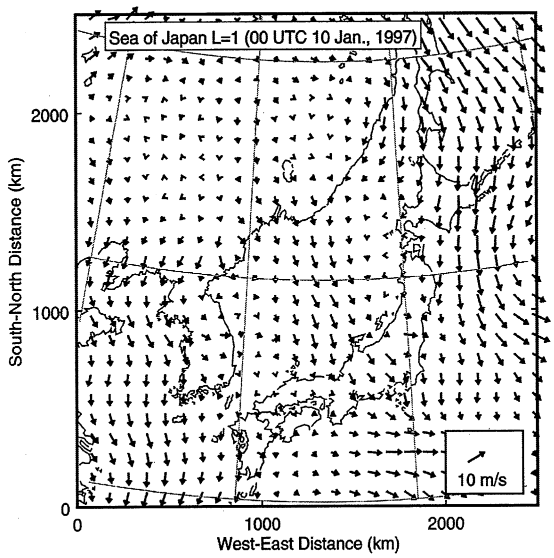
(2) Concentration Distribution

In the paper, all analyses by the WSPEEDI are performed under the condition that a radioactive nuclide of unit becquerel is released at the height of 75 m in 16 min near Vladivostok. The WSPEEDI has predicted space-time dependent concentration distributions of radioactive nuclides in air. In **Fig. 7**, the predicted ^{137}Cs concentration is shown at every 6 h after the time of release in the SNW. From the Fig. 7, it is seen that the radioactivity reaches Japan in about 18 h and the maximum radioactive concentration in the air is found to be about 1.4×10^{-14} Bq/m^3. **Figures 8** and **9** show the dispersion of radioactivity in the WNW and CW. In the same manner, ^{131}I, ^{133}I, ^{135}I, ^{137}Cs, ^{134}Cs and ^{90}Sr are released in the three wind conditions. For all of these radionuclides, distribution patterns of radionuclides with time are identical but the values of radioactive concentration are different due to half-lives. The traveling time of radionuclides from Vladivostok to Japan and Korea and the residence time of radioactive air over relevant country are listed in **Table 6** together with the maximum radioactive concentration of each nuclide in Japan and in Korea.

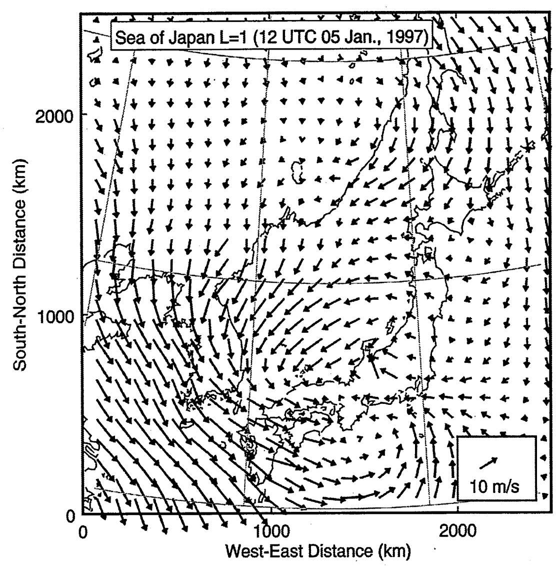
In the cases of SNW and WNW as seen Figs. 7 and 8, the radioactive air reaches the Sanin and the Hokuriku regions of Japan at first after 18 and 42 h of release respectively by traveling across the Sea of Japan and then passes over southern half part of the Honshu island. On the other hand, in the case of CW as seen in Fig. 9, radioactive nuclides reaches the eastern half of Korean



(a) Strong north wind



(b) Weak north wind



(c) Cyclonic wind

Fig. 6 Three wind patterns used for WSPEEDI analysis

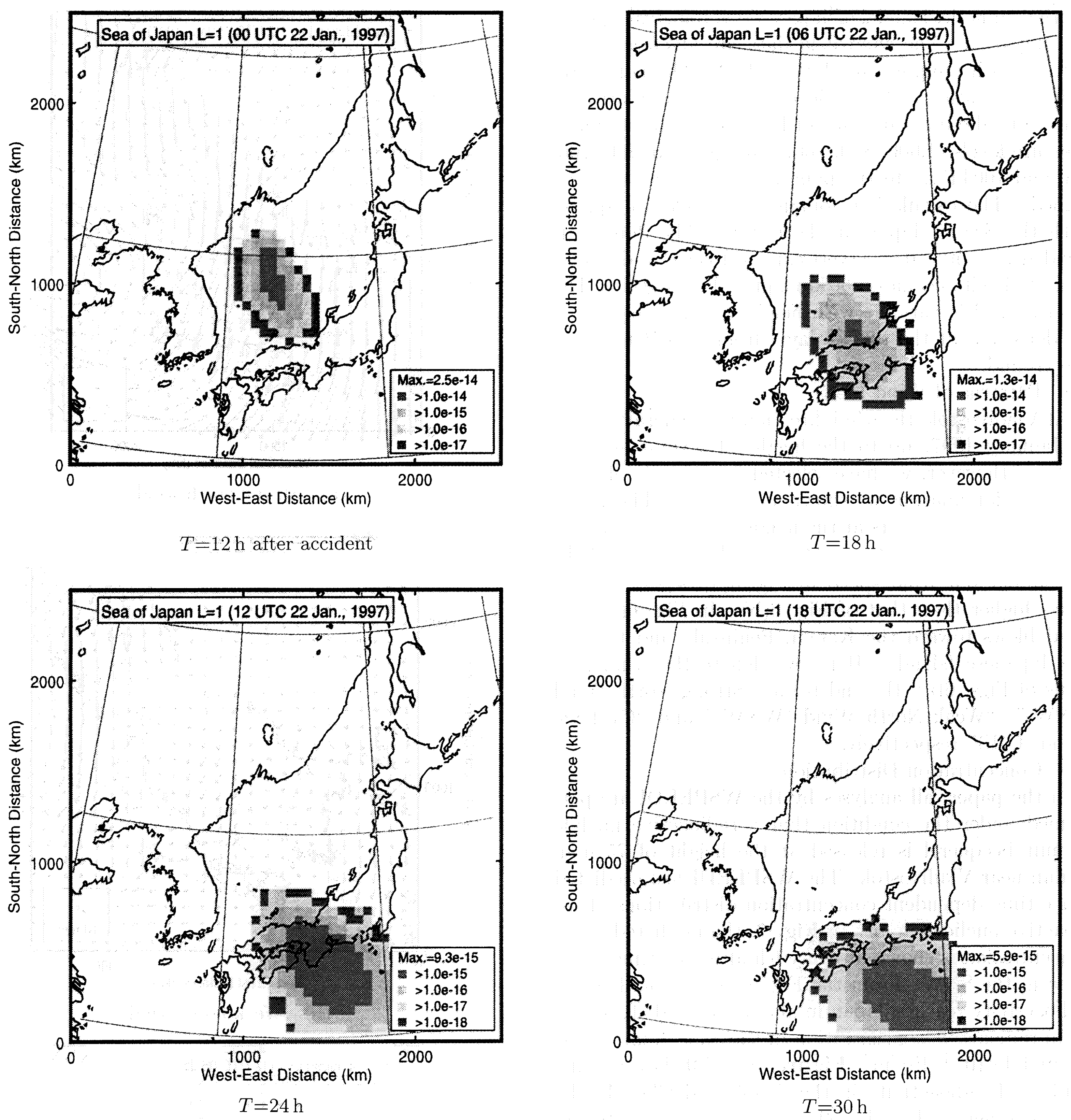


Fig. 7 Change of ^{137}Cs radioactivity in air with time in "Strong north wind" condition (Bq/m^3)

Table 6 Estimated maximum radioactivity in air near ground in Japan and in Korea (Bq/m^3) (1.0 Bq is released at Vladivostok.)

	Wind patters	Strong north wind	Weak north wind	Cyclonic wind	
	Affected country	Japan	Japan	Korea	Japan
	Traveling time (h)	18	42	30	30
	Residence time (h)	12	58	30	30
Chazhma Bay accident	^{131}I	7.2×10^{-15}	1.2×10^{-15}	5.1×10^{-15}	5.1×10^{-15}
	^{133}I	4.3×10^{-15}	1.8×10^{-16}	2.6×10^{-15}	2.6×10^{-15}
	^{135}I	1.2×10^{-15}	1.6×10^{-18}	4.8×10^{-16}	4.8×10^{-16}
Hypothetical reactivity accident	^{137}Cs	1.4×10^{-14}	6.9×10^{-15}	7.5×10^{-15}	7.5×10^{-15}
	^{134}Cs	1.4×10^{-14}	6.9×10^{-15}	7.5×10^{-15}	7.5×10^{-15}
	^{90}Sr	1.4×10^{-14}	6.9×10^{-15}	7.5×10^{-15}	7.5×10^{-15}

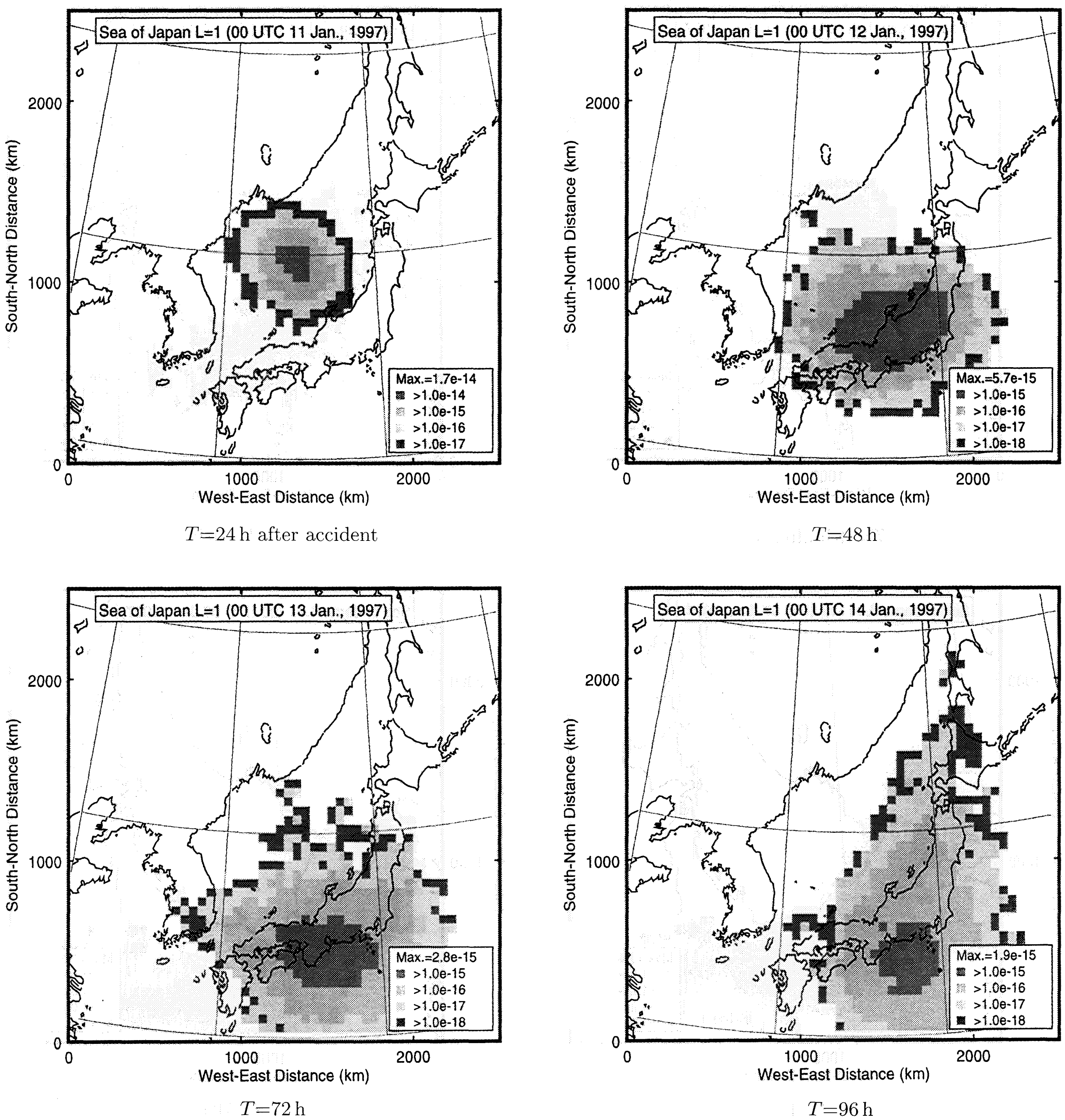


Fig. 8 Change of ^{137}Cs radioactivity in air with time in "Weak north wind" condition (Bq/m^3)

Peninsula and the Sanin region of Japan almost at the same time after 30 h of release and passes by after another 30 h crossing over whole Korean Peninsula and the Kyushu, Shikoku and Chugoku regions of Japan.

(3) Radiological Dose

The WSPEEDI code estimates internal and external radiological doses from obtained radiation concentrations in the air and on the ground. The radiological dose by an inhaled radionuclide is evaluated as an integrated dose over lifetime (70 yr) considering the biological half-life of the radionuclide. However, the WSPEEDI code does not evaluate the long-term external dose by radionuclides deposited on the ground and the internal dose by food chain, partly due to the fact that such doses can be easily avoided by social control.

For the three wind patterns, the external and the internal dose distributions are mapped as shown in **Figs. 10** and **11**, respectively. In these figures, it is supposed that ^{137}Cs of 1 Bq is released at Vladivostok. From the figure, the internal dose is found to be much higher than the external one due to the integrated dose over lifetime caused by ^{137}Cs whose half-life is 30.0 yr but whose biological half-life for one half of the cesium is for 2 d and for the other half is for 110 d. The effective half-lives are thus dominated by the biological half-lives. The maximum doses of the external and the internal are listed in

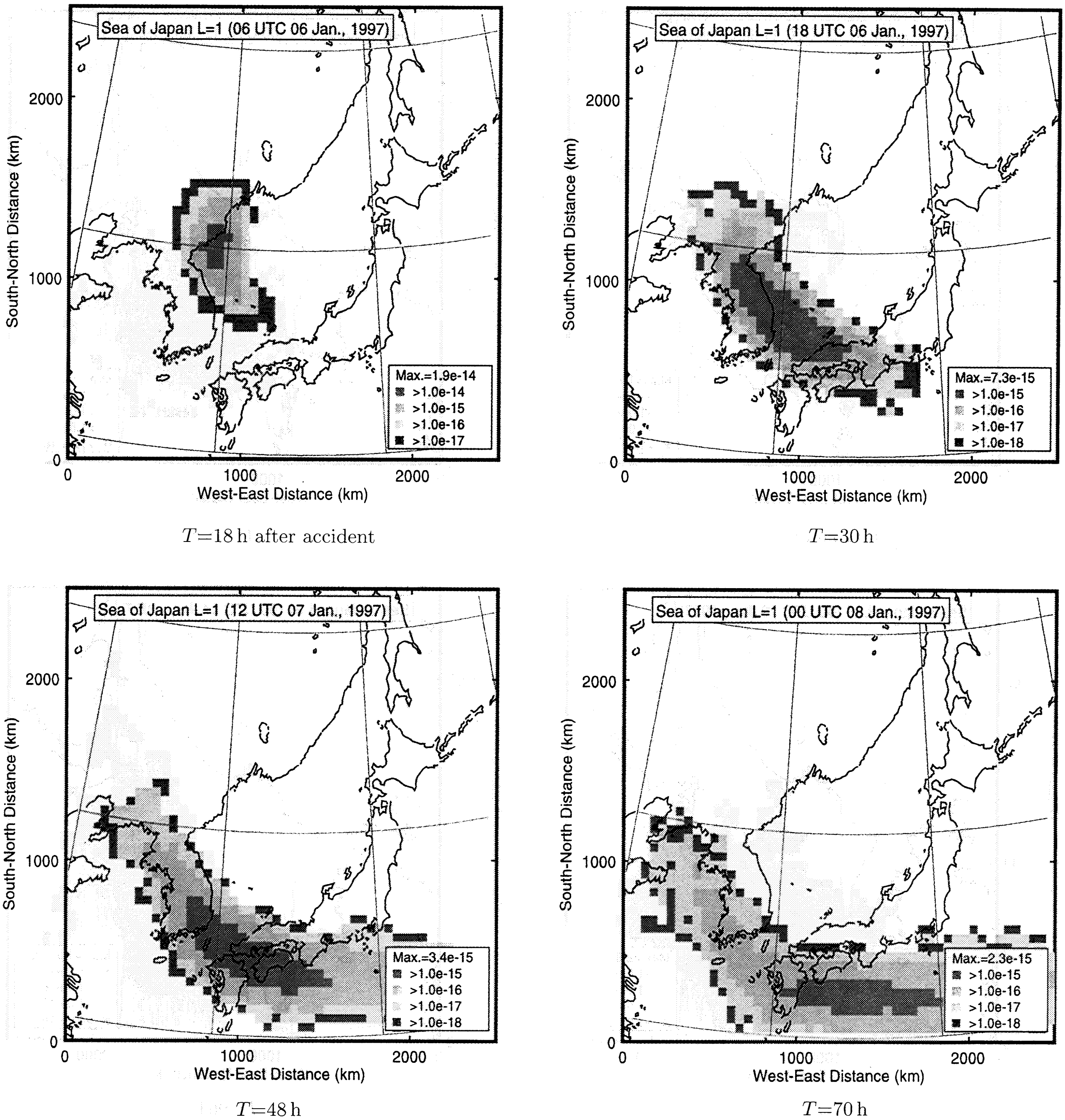


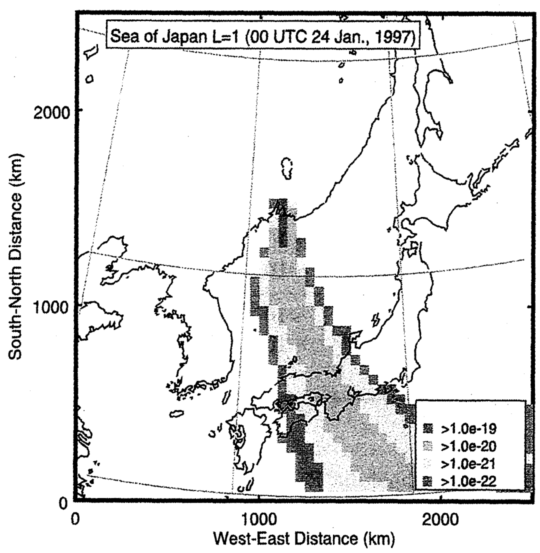
Fig. 9 Change of ^{137}Cs radioactivity in air with time in "Cyclonic wind" condition (Bq/m^3)

Table 7 for each radionuclide.

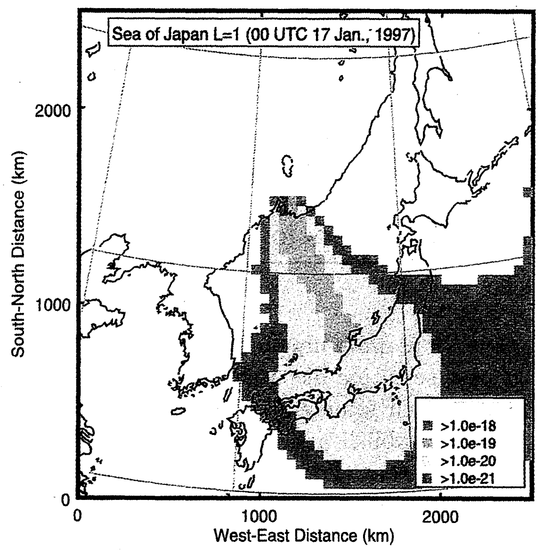
In the case of ^{137}Cs, ^{134}Cs and ^{90}Sr, the higher radioactive concentrations are seen in the case of SNW in Table 6, however, the values of estimated doses in Table 7 are similar to WNW. It can be explained by the relation of the concentration and residence time. The concentration of SNW is about 5 times higher than that of WNW but, on the contrary, the residences time of SNW is about 5 times smaller than that of WNW. Taking the decrease of the concentration by dispersion during the residence time into account, therefore, the values of dose in Table 7 for SNW and WNW for these isotopes are almost similar since the dose is considered as proportional to the concentration and to the residence time. However, in the case of short half-life isotopes, ^{131}I, ^{133}I and ^{135}I, the concentration decreases rapidly with time as seen in Table 6 and the maximum concentration and dose as well are observed in the case of SNW, although the dose values do not show significant differences due to the effect of the residence time.

4. Risk of Reactivity Accident to Neighboring Countries

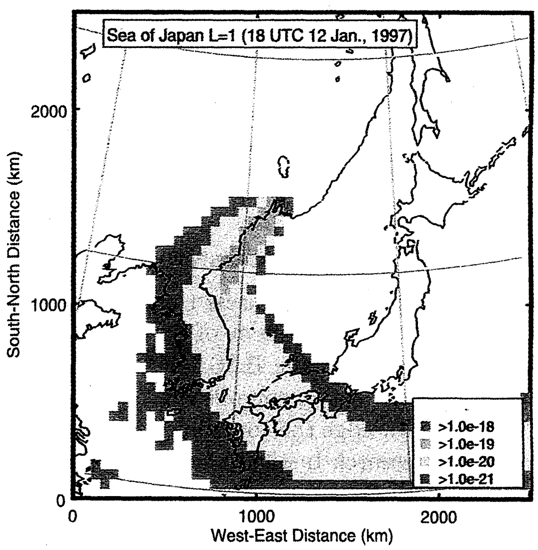
The radiological risk can be estimated by multiplying the values of Tables 4 and 5, and the values in Table 7 for each nuclide correspondingly. **Table 8** shows the es-



(a) Strong north wind

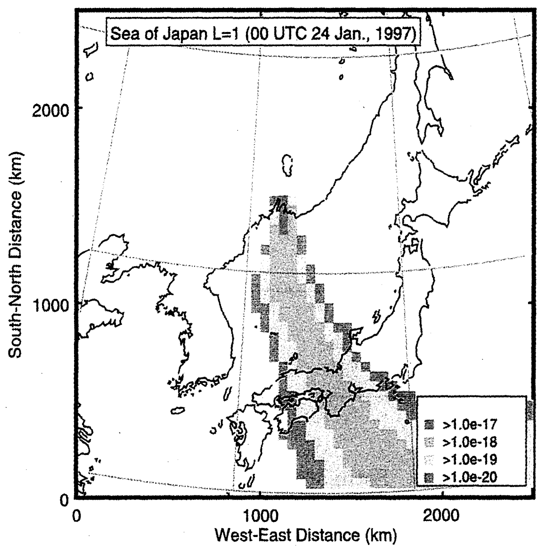


(b) Weak north wind

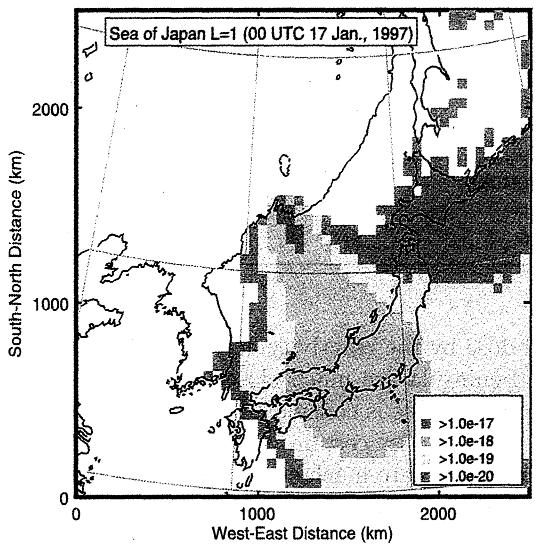


(c) Cyclonic wind

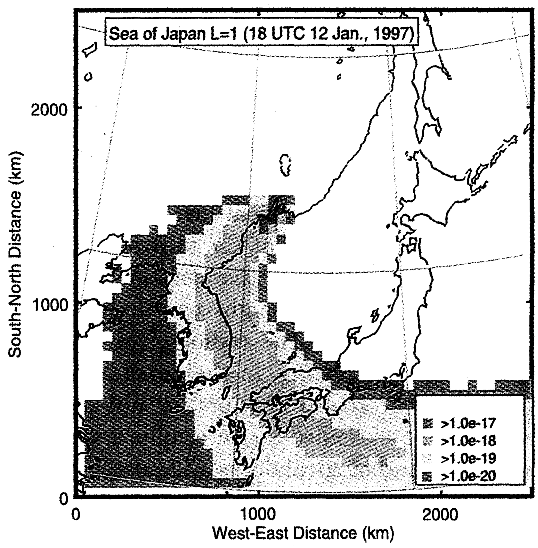
Fig. 10 Distribution of estimated external dose by ^{137}Cs (mSv)



(a) Strong north wind



(b) Weak north wind



(c) Cyclonic wind

Fig. 11 Distribution of estimated internal dose by ^{137}Cs (mSv)

Table 7 Estimated dose in affected area of Japan and Korea (mSv) (1.0 Bq is released near Vladivostok.)

	Wind pattern / Affected country	Strong north wind Japan		Weak north wind Japan		Cyclonic wind Korea		Cyclonic wind Japan	
	Dose (mSv)	External	Internal	External	Internal	External	Internal	External	Internal
Chazhma Bay accident	^{131}I	$\sim 10^{-20}$	$\sim 10^{-18}$	$\sim 10^{-20}$	$\sim 10^{-18}$	$\sim 10^{-20}$	$\sim 10^{-19}$	$\sim 10^{-20}$	$\sim 10^{-19}$
	^{133}I	$\sim 10^{-20}$	$\sim 10^{-19}$	$\sim 10^{-20}$	$\sim 10^{-20}$	$\sim 10^{-20}$	$\sim 10^{-20}$	$\sim 10^{-21}$	$\sim 10^{-20}$
	^{135}I	$\sim 10^{-20}$	$\sim 10^{-20}$	$\sim 10^{-22}$	$\sim 10^{-22}$	$\sim 10^{-21}$	$\sim 10^{-21}$	$\sim 10^{-21}$	$\sim 10^{-21}$
Hypothetical reactivity accident	^{137}Cs	$\sim 10^{-20}$	$\sim 10^{-18}$	$\sim 10^{-20}$	$\sim 10^{-18}$	$\sim 10^{-20}$	$\sim 10^{-18}$	$\sim 10^{-20}$	$\sim 10^{-18}$
	^{134}Cs	$\sim 10^{-20}$	$\sim 10^{-18}$	$\sim 10^{-19}$	$\sim 10^{-18}$	$\sim 10^{-19}$	$\sim 10^{-18}$	$\sim 10^{-20}$	$\sim 10^{-19}$
	^{90}Sr	—	$\sim 10^{-17}$	—	$\sim 10^{-17}$	—	$\sim 10^{-18}$	—	$\sim 10^{-18}$

Table 8 Estimated dose in affected area of Japan and Korea (mSv) (Chazhma Bay and Hypothetical reactivity accidents)

	Wind pattern / Affected country	Strong north wind Japan		Weak north wind Japan		Cyclonic wind Korea		Cyclonic wind Japan	
	Dose (mSv)	External	Internal	External	Internal	External	Internal	External	Internal
Chazhma Bay accident	^{131}I	$\sim 3\times 10^{-10}$	$\sim 3\times 10^{-8}$	$\sim 3\times 10^{-10}$	$\sim 3\times 10^{-8}$	$\sim 3\times 10^{-10}$	$\sim 3\times 10^{-9}$	$\sim 3\times 10^{-10}$	$\sim 3\times 10^{-9}$
	^{133}I	$\sim 6\times 10^{-9}$	$\sim 6\times 10^{-8}$	$\sim 6\times 10^{-9}$	$\sim 6\times 10^{-9}$	$\sim 6\times 10^{-9}$	$\sim 6\times 10^{-9}$	$\sim 6\times 10^{-10}$	$\sim 6\times 10^{-9}$
	^{135}I	$\sim 2\times 10^{-8}$	$\sim 2\times 10^{-8}$	$\sim 2\times 10^{-10}$	$\sim 2\times 10^{-10}$	$\sim 2\times 10^{-9}$	$\sim 2\times 10^{-9}$	$\sim 2\times 10^{-9}$	$\sim 2\times 10^{-9}$
Hypothetical reactivity accident	^{137}Cs	$\sim 4\times 10^{-6}$	$\sim 4\times 10^{-4}$	$\sim 4\times 10^{-6}$	$\sim 4\times 10^{-4}$	$\sim 4\times 10^{-6}$	$\sim 4\times 10^{-4}$	$\sim 4\times 10^{-6}$	$\sim 4\times 10^{-4}$
	^{134}Cs	$\sim 4\times 10^{-7}$	$\sim 4\times 10^{-5}$	$\sim 4\times 10^{-6}$	$\sim 4\times 10^{-5}$	$\sim 4\times 10^{-6}$	$\sim 4\times 10^{-5}$	$\sim 4\times 10^{-7}$	$\sim 4\times 10^{-6}$
	^{90}Sr	—	$\sim 7\times 10^{-4}$	—	$\sim 7\times 10^{-4}$	—	$\sim 7\times 10^{-5}$	—	$\sim 7\times 10^{-5}$

timated dose by the reactivity accidents. China and the Korean Peninsula are much closer to Vladivostok than Japan and the dose is considered to become much larger in these areas under certain wind conditions. The dose values in Table 8 are much smaller than the annual dose from the naturally occurring radiation in the environment, although the reactivity accident of the reactors with spent fuel might have potentially hazardous consequences to neighboring countries since the evaluations of hot-spot, long-term external dose and food chain are omitted in the paper.

IV. Conclusions

In the paper, the reactivity accident of a Russian submarine near Vladivostok has been discussed and analyzed. The analyses with typical meteorological conditions in winter have shown that the radioactive material might be transported through the atmosphere to Japan in one to several days and might contaminate a wide area of Japan. However, the radiological dose to the area might be not significant. In the paper, the effect of precipitation which creates hot-spots is not considered. Our study will be extended to determine how the precipitation affects radiological doses and how it affects the food-chain and deposited radionuclides in the long term.

The reactivity accident is assumed to occur during refueling and defueling nuclear reactors of submarines. These operations are usually under military control and we have almost no official channel to discuss such issues. However, it is quite urgent to have an official channel for at least scientific discussions, and we hope that the group of nuclear scientists, such as members of this Society, would establish a sort of scientific forum with Russian counterparts to find solutions to these problems. Without establishing a scientific channel, it is almost impossible to study this subject due to the absence of key information. Further, it is quite essential to have a forum for scientific discussion on these issues participated in by scientists from Russia and neighboring countries. Because nuclear submarine accidents are threatening to neighboring countries, it is important that the scientific results are reviewed by scientists from Russia and neighboring countries so that errors can be avoided and misunderstandings which might results in a threat to another country can be reduced.

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