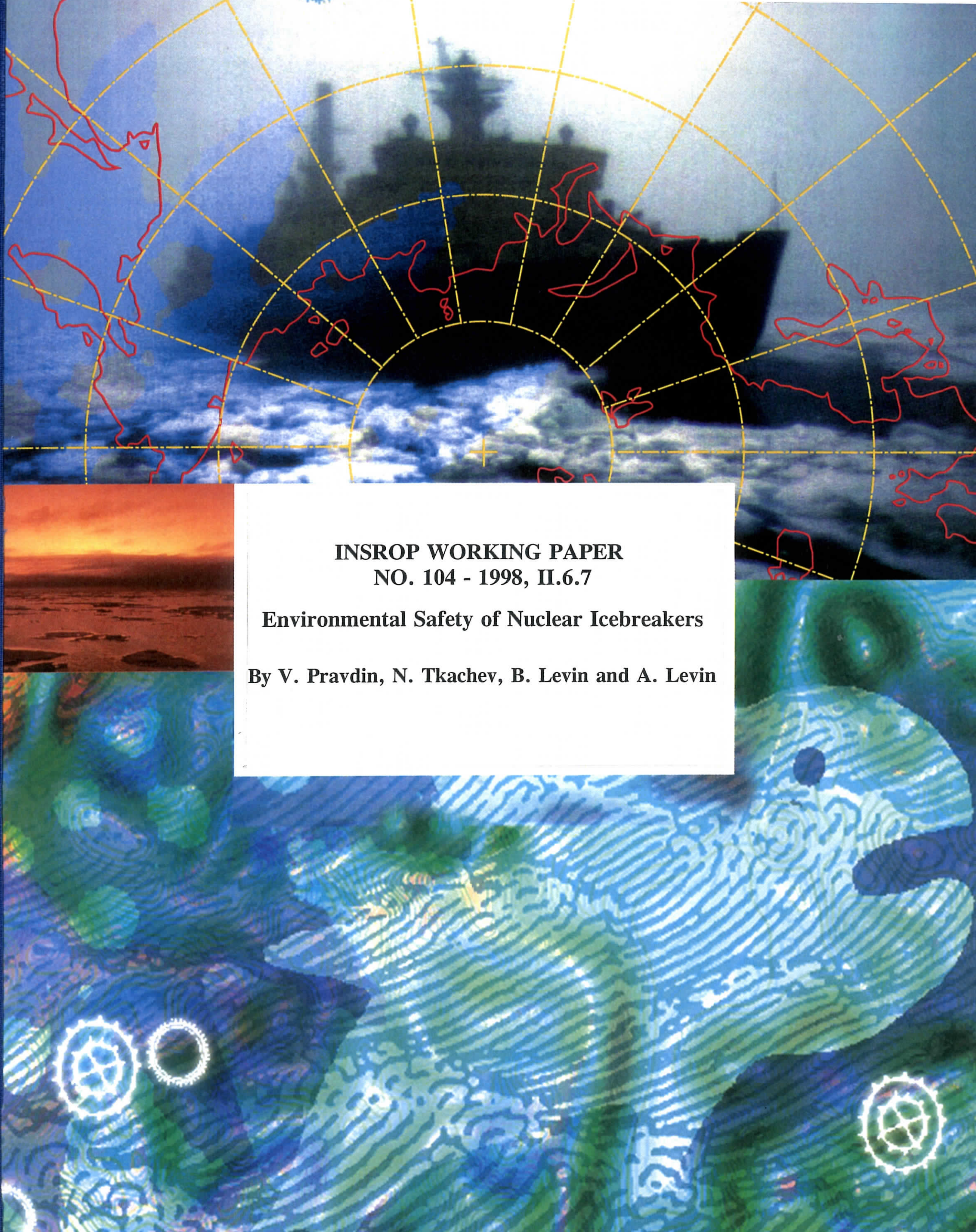

# INSROP WORKING PAPER
# NO. 104 - 1998, II.6.7

# Environmental Safety of Nuclear Icebreakers

By V. Pravdin, N. Tkachev, B. Levin and A. Levin

**INSROP International Northern Sea Route Programme**

Central Marine
Research & Design
Institute, Russia

The Fridtjof
Nansen Institute,
Norway

Ship and Ocean
Foundation,
Japan

International Northern Sea Route Programme (INSROP)

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Nansen Institute,
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# INSROP WORKING PAPER NO. 104-1998

Sub-programme II: Environmental Factors

Project II.6.7: Environmental Safety of Nuclear Icebreakers

Supervisor: Vladimir Pravdin

**Title:** **Environmental Safety of Nuclear Icebreakers**

**Authors:** **V. Pravdin, N. Tkachev, B. Levin and A. Levin**

Address: Central Marine Research and Design Institute (CNIIMF),
Kavalergardskaya Street 6, 193 015 St.Petersburg,
RUSSIA

Date: 28 July 1998

Reviewed by: Professor Kaj Riska, Ship Laboratory, Helsinki University of Technology, Helsinki, FINLAND, and

Professor Povl L. Ølgaard, Department of Physics, Technical University of Denmark, Lyngby, DENMARK.

## *What is an INSROP Working Paper and how to handle it:*

## FOREWORD - INSROP WORKING PAPER

INSROP is a five-year multidisciplinary and multilateral research programme, the main phase of which commenced in June 1993. The three principal cooperating partners are **Central Marine Research & Design Institute (CNIIMF)**, St. Petersburg, Russia; **Ship and Ocean Foundation (SOF)**, Tokyo, Japan; and **Fridtjof Nansen Institute (FNI)**, Lysaker, Norway. The INSROP Secretariat is shared between CNIIMF and FNI and is located at FNI.

INSROP is split into four main projects: 1) Natural Conditions and Ice Navigation; 2) Environmental Factors; 3) Trade and Commercial Shipping Aspects of the NSR; and 4) Political, Legal and Strategic Factors. The aim of INSROP is to build up a knowledge base adequate to provide a foundation for long-term planning and decision-making by state agencies as well as private companies etc., for purposes of promoting rational decisionmaking concerning the use of the Northern Sea Route for transit and regional development.

INSROP is a direct result of the normalization of the international situation and the Murmansk initiatives of the former Soviet Union in 1987, when the readiness of the USSR to open the NSR for international shipping was officially declared. The Murmansk Initiatives enabled the continuation, expansion and intensification of traditional collaboration between the states in the Arctic, including safety and efficiency of shipping. Russia, being the successor state to the USSR, supports the Murmansk Initiatives. The initiatives stimulated contact and cooperation between CNIIMF and FNI in 1988 and resulted in a pilot study of the NSR in 1991. In 1992 SOF entered INSROP as a third partner on an equal basis with CNIIMF and FNI.

The complete series of publications may be obtained from the Fridtjof Nansen Institute.

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- Norwegian Polar Research Institute
- SINTEF (Foundation for Scientific and Industrial Research - Civil and Environmental Engineering), Norway.

## PROGRAMME COORDINATORS

- **Yury Ivanov, CNIIMF**
  Kavalergardskaya Str.6
  St. Petersburg 193015, Russia
  Tel: 7 812 271 5633
  Fax: 7 812 274 3864
  E-mail: cniimf@neva.spb.ru

- **Willy Østreng, FNI**
  P.O. Box 326
  N-1324 Lysaker, Norway
  Tel: 47 67 11 19 00
  Fax: 47 67 11 19 10
  E-mail: sentralbord@fni.no

- **Hiroyasu Kawai, SOF**
  Senpaku Shinko Building
  15-16 Toranomon 1-chome
  Minato-ku, Tokyo 105, Japan
  Tel: 81 3 3502 2371
  Fax: 81 3 3502 2033
  E-mail:sofkawa@blue.ocn.ne.jp

## Project Team

The Project team consisted of the following:

| | | |
|---|---|---|
| Dr. V. Pravdin | leader of Project, | CNIIMF |
| Dr. N. Tkachev | | CNIIMF |
| Dr. B. Levin | | CNIIMF |
| Eng. A. Levin | | CNIIMF |

## Summary

**Key words:** control, radiation, nuclear icebreaker, safety systems, Arctic basin, emergency plan, emergency party.

The Reports (Parts I and II) dealing with environmental safety of nuclear icebreakers in the Arctic (Sub-Program II of INSROP. Environmental Safety) present results of a conservative assessment of the impact produced by radiation components of an icebreaker nuclear accident on the personnel, population and environment. The Reports show that in case of an accident contemplated in the technical documentation radiological situation on board the icebreaker and in the nearest surroundings is within the sanitary standards. In case of an accident not contemplated in the technical documentation radiation impact on the ecological systems differs from the normative values. In this case a package of organisational and engineering and managerial decisions is needed to mitigate that impact on the personnel, population and environment to an acceptable low level.

The aim of this work is to investigate the environmental safety of using the Russian nuclear icebreaker in Arctic shipping under the International Northern Sea Route Programme.

Practical experience gained in safe operation of "Rossia" and "Taimyr" type nuclear icebreakers verifies the high quality of the nuclear power plants used in the icebreakers as well as the high qualification and professional training of the personnel wich makes it possible to operate the plants trouble free.

The proper technical condition of the nuclear powered ships and personnel safety on board them is ensured in compliance not only with the requirements of the national but also with those of the international documents, such as:

- IMO Resolution A.491(12). Code of Safety for Nuclear Merchant Ships. 19.11.1981.
- A Report by the International Nuclear Safety Advisory Group of the IAEA (No.75-INSAG-3).
- IMO Resolution A.741(18). International Management Code for the Safe Operation of Ships and For Pollution Prevention (ISM Code). 04.11.1993.
- IMO Resolution A.788(19). Guidelines on Implementation of the International Safety Management (ISM) Code of the Administrations. 23.11.1995.

- Safety Management Manual. SMS - 001. Safety Management System, Murmansk Shipping Company. 1997.

The icebreakers are operated in accordance with the fundamental safeguarding principles:

- managerial principles including establishment of safety culture, responsibility of operating organisation, checking of the fleet's operational activity involving safeguarding;
- principles of structural defence in depth including organisational and technical measures to prevent nuclear - and radiohazardous accidents and mitigate their after-effects on the personnel and environment;
- technical principles including tried engineering activity, good marine practice, proper training and qualification of personnel, crew members, continuous evaluation of the NPP technical condition, radiation protection, generalisation and use of operating experience.

In compliance with the requirements of the service and technical documentation and requirements set forth below, Russian legislation relating to use of atomic energy in Russia, the Operating Organisation (Shipowner`s Administration) plans and puts into effect a package of precautionary measures to ensure safe operation of the Fleet and maintain appropriate readiness to mitigate negative consequences of an accident the likelihood of which is low but can not be completely precluded.

As the result of an analysis made to assess possible after-effects of the icebreaker nuclear accident proposals have been worked out to establish informational support to the accident control process and to design organisational and technical measures to minimise radiation impact produced by the accident.

However, for the purpose of the international shipping in compliance with the INSROP program use of the informational support of the existing Marine due to linguistic differences in the software, routing of information flows and lack of the used program adaptation protocols.

With the aim of informational support to the international navigation in the Arctic, assisted by the Russian icebreakers, work shall be performed within the INSROP framework to eliminate the above differences, which hinder integration of the information systems. The requirements of the Federal Law as applied to the international exchange of information on nuclear accidents shall be taken into account.

The list of top priority works on integration of the Russian and INSROP information systems is given In Appendix 3, Part II.

## CONTENT

# Environmental Safety of Nuclear Icebreakers, Part I

# LIST OF ABBREVIATIONS

| | |
|---|---|
| CG | - reactivity control rod groups |
| EFP | - emergency feed pump |
| EPS | - electrical propulsion system |
| GD | - guidance document |
| INSROP | - International Northern Sea Route Programme |
| LCN | - local computer network |
| NPP | - nuclear propulsion plant |
| NSSS | - nuclear steam supply system |
| PCP | - primary circulating pump |
| SG | - steam generator |
| STS | - steam turbine system |
| RCR | - reactor control room |
| USARMS | - Unified State Automated Radiation Monitoring System |

# INTRODUCTION

The feature of navigation in the Arctic seas is the need to use the nuclear icebreakers of "Rossia" and "Taimyr" type that provide regularity and safety of navigation along the Northern Sea Route.

The operating experience of the Russian nuclear icebreakers since 1960 shows that the probability of a nuclear or a heavy radiation accident is extremely low. Within the specified period of time there were no incidents entailing over-irradiation of people or environmental contamination outside the limits prescribed for normal operation.

## *To estimate of the risk for environment*

Failure statistics of powerplants at sea confirm relatively high reliability of NPPs on the whole as well as their basis components, which is much better than the average values for diesel power plants (Table I.1).

*Table I.1.*

**Reliability Criteria of NPPs of "Arctica"-type Icebreakers**

| Criteria | NPP | Component Systems | | |
|---|---|---|---|---|
| | | NSSS | STS | EPS |
| Mean time to emergency stop at sea, $1 \cdot 10^3$, 1/h | 3.4 | 0.2 | 1.4 | 1.5 |
| Mean recovery time, $1 \cdot 10^2$, 1/h | 35.7 | 22.2 | 45.5 | 26.3 |

Time to emergency stop at sea due to reasons related to the NPP (abt. 300 h for NPPs in general, abt. 700 h for EPS and steam turbine system (STS), and abt. 5600 h for NSSS, with recovery times, respectively, abt. 3; 4; 2; and 4.5 h) is determined primarily by malfunctions in cooling sea water supply under ice conditions (abt. 60% of all failures) and by failures in STS control systems. The reactor scram takes place as seldom as once a year on the average per reactor and relates mostly to the modes of the NSSS start-up. And not a single emergency case resulted in an aggravated radiation situation onboard or to personnel radiation overdosing.

The NPP reliability data quoted above are, on the one hand, the result of high quality of the equipment , of a sufficient (and even excessive, for certain systems) degree of redundancy, and of strict fulfilling of maintenance procedures. On the other hand, they require serious attention to further improvement of seawater intake design (ice chests and intake gratings) and cooling system structure, and to the improvements in the design and structure of monitoring and control systems.

Mean annual labour requirements for NPP maintenance both in operation and under base conditions, carried out mostly (85% to 90%) by highly skilled shipboard personnel, is approx. 1600 man-hours per 1 MW of NPP rated output; this is 1.4 to 1.7 times lower than for today's diesel-electric icebreakers, and related mostly (more than by half) to STS and EPS systems.

Replacing the strictly calendar scheduled maintenance with the preventive servicing of STS end EPS equipment and some NSSS subsystems by their actual technical state, on the basis of wide use of equipment diagnostics facilities (mainly by acoustic emission and vibration measurement methods), provides possibilities to reduce maintenance labour by 20-25% and to relieve ships' crews; for the time being, these possibilities are not used to a sufficient extent.

The purpose of this work is to analyse environmental safety (radiation component) assurance in using the nuclear icebreakers of the Russian Federation in navigation under the International Northern Sea Route Programme.

1. The nuclear icebreakers have been designed and built under supervision of the Register of the USSR, Supervisory Bodies of the Ministry of Merchant Marine, Ministry of Public Health and State Committee for Supervision over the Safety of Work in Nuclear Power Engineering of the USSR in compliance with the requirements of such documents as:

- "Rules for the Classification and Construction of Nuclear Ships", Register of the USSR;
- "International Convention for the Safety of Life at Sea" as applied to the nuclear ships;
- "Rules for the Nuclear Safety of the Marine Nuclear Power Plants";
- "Radiation and Health Requirements for the Nuclear Ships";
- "Radiation Safety Standards";
- "Basic Sanitary Rules".

Workmanship in manufacturing and installation of the power equipment, results of the dockside and sea trials of the power plant and nuclear icebreakers have been documented in the acceptance certificates and the USSR Register's documents specified by the relevant international conventions.

The crews of the nuclear icebreakers have been manned by specialists who have an appropriate professional training and practical experience in operation of ships with nuclear power plants.

Organisation of the service on board the Russian icebreakers complies with the requirements set forth in the "Supplement to the Regulations for Service on board the ships of the Ministry of Merchant Marine of the USSR. Nuclear ships and Nuclear Support Ships". The above "Supplement..." specifies responsibilities, rights and duties of persons who attend continuously and directly the marine nuclear power plants and contains their duty.

The nuclear icebreakers are operated in compliance with the "Supplement to the

Regulations for engineered Marine Operation. Nuclear ships and Nuclear Support Ships" which prescribes specific features of operation such as: base conditions, repair and maintenance, organisation of potentially nuclear- and radiation-hazardous work.

2. The nuclear propulsion plant has been so designed and arranged on board the icebreaker as to ensure protection of the crew members, public and environment against radiation exposure both in normal operation and during design basic accidents by setting up successive barriers in the potential outlet paths of radioactive substances. Safety of the plant is ensured by devices and systems for normal operation as well as safety systems intended for reliable shutdown of the nuclear reactor, cooling the core and limitation of the accident consequences. In particular, among the safety systems are:

- reactor control and protection systems;
- residual heat removal system;
- emergency core cooling system;
- containment pressure suppression system.

Functioning of the propulsion plants of the icebreakers is maintained by the ship's systems:

- power supply (electric power, working media);
- automatic and remote control and monitoring of machinery and devices;
- data and computing;
- radiation dosimetry and monitoring.

The above devices and systems maintain safe operation of the nuclear propulsion plants, satisfying the single failure criterion.

The icebreakers currently in operation carry pressurised water reactors which have a negative temperature reactivity coefficient of moderator (coolant) and negative temperature coefficient of nuclear fuel (Doppler effect). The said fact is a powerful means to maintain the reactor in safe condition.

3. All-the-year-round navigation in the Arctic seas is supported by the appropriate number of nuclear icebreakers available on the Northern Sea Route, depending on the climatological, seasonal, hydrometeorological and ice conditions, composition and structure of the convoy.

In view of the fact that development of an emergency situation on board the nuclear icebreaker is an event of random nature in terms of time and space, which depends on many factors (technical condition of the plant, qualification of the personnel, natural, ice, hydrometeorological, navigational conditions etc.), potential radiation exposure can affect vast area from the Barents Sea to Bering Straits.

The port calling procedure for the nuclear ships is governed by appropriate IMO and IAEA recommendations and "Rules for Radiation Safety of the Sea Trade Ports of the USSR when Visited by Nuclear Merchant Ships", based on the icebreaker safety data with due regard for hydrometeorological conditions of the point of call the ship will be allotted basic berth or anchoring place as well as an additional remote berth in accordance with the port emergency plan for use in case of an emergency.

As a rule the Port Administrations have no Radiation Safety Services at their disposal and in such a case the Emergency Plan provides for use of the shipboard radiation dosimetry and monitoring facilities. The Plan provides also for introduction of limited (supervised area) or controlled access areas in the event of radiation accident.

4. The Russian nuclear icebreakers have been provided with an advanced information complex, which makes it possible to assess the radiological situation both under normal and emergency sailing conditions.

There is service and engineering documentation specifying action of the crew under extreme conditions and procedure for notification of the appropriate administrative arrangements about the incident occurred. Work is underway to integrate the shipboard local computing networks into a single information system which will make it possible not only to record the actual situation but also to predict development of the accident and to work out and take on that basis a best decision as to confine the accident and eliminate its consequences.

The INSROP project contemplates development of an information system (definition of database contain and establishment of a infrastructure required for functioning of same) to the interests of international shipping along the Northern Sea Route. The process of creating such a system should incorporate joint development of specific requirements as applied to organisation of protocols for entry into the communication information subsystems to be developed under the INSROP project, use of similar charts for conjunction of the geographical data, unified standards for communication channel hardware.

# 1. ACCIDENTS ASSOCIATED WITH NPP MALFUNCTIONS

Among the after-effects of NPP and NSSS malfunctions may be emergency rise of the neutron power, pressure and temperature within primary coolant system, reduction or failure of core heat removal. Development of emergency situations caused by such malfunctions is confined by safety systems facilities stipulated by the project, which are automatically actuated.

The purpose of analysis of accidents is to identity variation range of data and parameters defining the NPP condition. If the results of the analysis show that during the accident no data fall outside the limits set from strength considerations and reliable core cooling is achieved this is to be taken to mean that such developments entail no radiation after-effects and do not affect environmental safety of the nuclear icebreaker.

The main means to prevent development of malfunction and confine same when the data reach safety limits are:

- actuation of the reactor shut-down system (scram);
- extreme reduction of the reactor power;
- cut-out of failed equipment and actuation of the stand-by and emergency items of the safety equipment.

When the reactor emergency protection comes into action the following operations will be automatically performed:

- emergency control rod groups insert with an emergency velocity into the core to a certain position;
- emergency and stand-by electric power sources are started;
- feed valve closes at a closing rate of 5% per second up to 5% of the rated flow rate;
- all the PCP change to low speed;
- non- essential steam and electric power loads are cut off;
- emergency and stand-by feed pumps are started.

When the reactor power is urgently reduced from alarm signals operated on PCP trip, main condenser failure, excessive consumption of feed water the following actions are automatically initiated:

- feed valve closes at a closing rate 5% per second up to preset position;
- reactivity control rod groups insert with an emergency velocity into the core;
- reactor power become stable at a preset level.

The results of analysis of the emergency situations caused by the NPP and NSSS malfunctions, made on condition that the initial event is taken to be the failure of normal operation device, coincident with the single failure of safety system which operation is needed under these conditions or the operator error are given in Table 1.1.

As an example, Fig. 1.1 and 1.2 show time variations in data characteristic of the NSSS state in a "Taimyr" type icebreaker during emergency incidents caused by uncontrolled introduction of positive reactivity for the alternatives: when the plant runs at 100% and 10% power respectively. It was assumed in the process of analysis that in consequence of a fault in the automation system the most efficient reactivity control rod group that moves to the topmost position and the operator did nothing to stop this.

Withdrawal of the CG during power operation results in generation of warning signals related to power, pressure and temperature (operation at 100% power) or solely to primary circuit pressure (operation at 10% power) with the normally functioning CG lowering to compensate increased reactivity and parameter divergence.

The analysis of the accident (Fig. 1.1, 1.2) shows that the reactor data do not fall, throughout the transient process, outside the acceptable values.

Despite the fact that in the emergency situations under consideration the reactor data lie within the acceptable limits the possibility of depressurisation of the primary pressure boundary due to hidden flaws cannot be completely ruled out. Accidents involving loss of leaktightness in the primary pressure boundary and assessment of after-effects of same will be discussed in the next section.

Fig.I.I. Variation of the NSSS characteristics with time – t, s when positive reactivity introduced uncontrollably; plant runs at I00% power

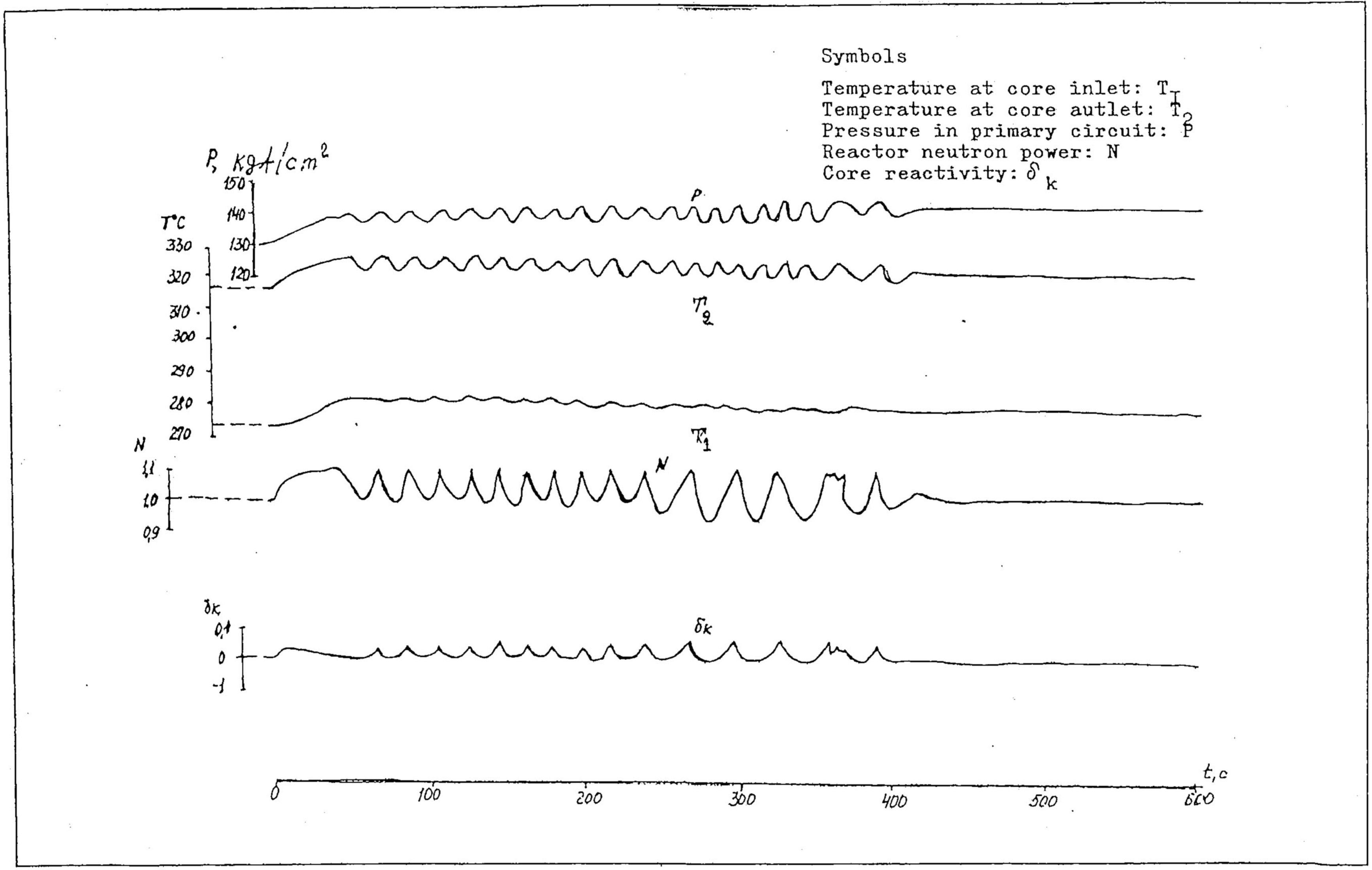

Fig.I.2. Variation of the NSSS characteristics with time – t, s when positive reactivity introduced uncontrollably; plant runs at I0% power

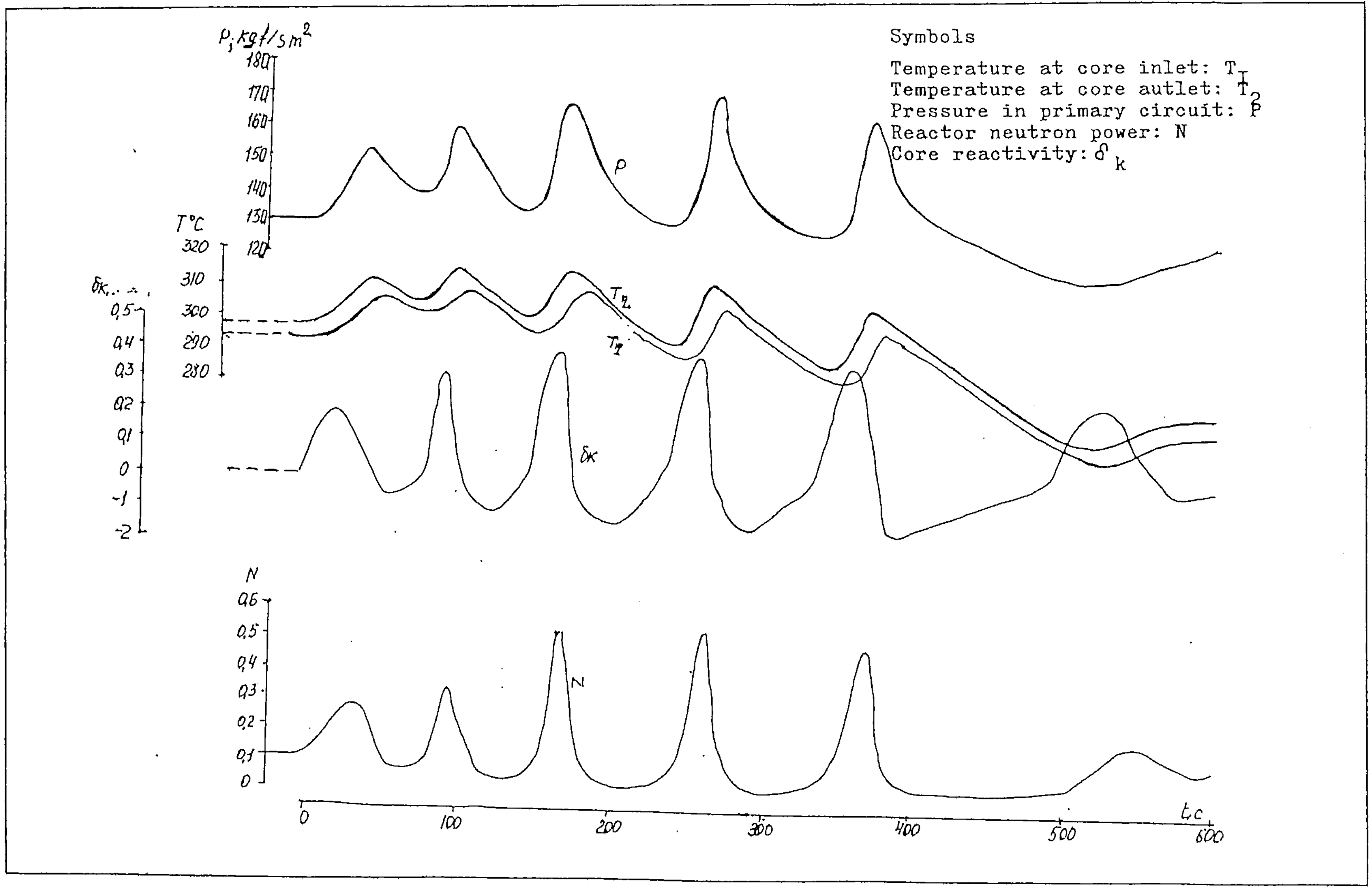

Table 1.1.

**Analysis of Emergency Situations Caused by NPP Malfunctions.**

| Emergency situation | Initial events | Safety systems actuation | Possible after-effects | Analysis results |
|---|---|---|---|---|
| 1. Failure of feed water supply to SG | Main feed water pipeline ruptured over a common portion with emergency feed water pipeline; filter cooler has not connected up in cooling mode. | Reactor scram actuation, EFP starting. | Upon reactor scram actuation, primary coolant temperature and pressure rise due to deficient core heat removal. | Maximum pressure value does not go over the limiting ones (210 to 220 kgf/sq.cm) and in 6000 s will amount to 172 kgf/sq.cm.<br>Reliability of the core is assured. The operator has sufficient time at his disposal to detect causes of the accident and take safety measures. |
| 2. Failure of electric power supplies. | Failure of main sources or switchboards (PCP shutdown). | Reactor scram actuation, starting of emergency and stand-by sources, starting of EFP, PCP, third circuit pumps. | Primary coolant pressure and temperature rise, short-time interruption of forced circulation in the primary coolant system and feed water supply. | Divergence of parameters is within the acceptable limits, NSSS is reliably cooled down. |
| 3. Rupture of main steam line. | Failure of steam and electric power supplies. | Reactor scram actuation, starting of emergency and stand-by electric power sources, EFP and PCP at low speed. | Short-time complete loss of power and failure of forced circulation in the primary coolant system. Primary coolant pressure and temperature rise. | Divergence of parameters is within acceptable limits. NSSS is reliably cooled down. |

| **Emergency situation** | **Initial events** | **Safety systems actuation** | **Possible after-effects** | **Analysis results** |
|---|---|---|---|---|
| 4. Uncontrolled reactivity variation. | | | Introduction of positive reactivity. | |
| 4.1. Uncontrolled withdrawal of the most efficient reactivity control member out of the core. | Occurrence of more than two simultaneous failures in the electromechanical elements and control circuits of CG, failures in the warning alarm and emergency protection equipment, coupled with operator errors. | Reactor scram actuation from a signal operated when emergency neutron power value has bean reached. | Rise of neutron power and primary coolant system pressure. | Neutron power increase does nor exceed 22% to 28% values, pressure does not increase acceptable value. |
| 4.2. Injection of cold water into core during PCP starting. | Starting of stopped PCP with leaks occurring through closed cut-off valve of the cutout SG. | Reactor scram actuation from a signal operated when emergency neutron power value has been reached. | Rapid rise of neutron power. | Reactor scram actuation shifts the reactor to subcritical state reliably. |
| 4.3. Sharp pressure drop in main steam line. | Rupture of steam line; instantaneous pressure drop down to the atmospheric pressure, uncontrolled increase of feed water flow rate. | Actuation of warning alarm to evidence neutron power rise, limitation of power'by means of introducing CG into the core. | Rice of neutron power and temperature at the core outlet. | Reactor power does not exceed 112%; divergence of other parameters is within acceptable limits; reactivity occurrence is compensated by controls. |

# 2. LOSS OF LEAKTIGHTNESS OF THE NSSS PRIMARY CIRCUIT

The most radiation-hazardous accidents of a nuclear propulsion plant on board an icebreaker which can affect adversely regularity of the Arctic shipping lines along the Northern Sea Route are those accidents which involve loss of leaktightness of the reactor primary circuit.

In case such an accident occurs the automatically actuated safety systems ensure scram, emergency core cooling and residual heat removal.

As a result, water level in the reactor is maintained not lower than the upper limit of the core, which prevents fusion of the fuel elements. Insertion of emergency and reactivity control rods provides assured shift of the reactor to subcritical state.

2.1. Loss of leaktightness of the primary circuit with the coolant steam-and-gas mixture passing into the containment results in a situation where the containment vessel filled with such a mixture becomes a volume source of ionising radiation.

Table 2.1 lists the isotopic composition of the primary coolant fractions as a function of duration of the reactor continuous operation. The composition shown has been obtained from the analysis of statistical data on the content of nuclear fuel fission products in the primary coolant inventory over a long operating period of icebreakers.

Calculations made in the CNIIMF's work "Development of an Automated Marine Radiation Monitoring System within the Scope of the Unified State Automated Radiation Monitoring System" show that activity of such a volume source degrades with time due to decay of the short-lived isotopes and operation of the closed ventilation and purification system.

Table 2.2 lists radiation power values from the containment volume filled with steam-and-air phase of the primary coolant inventory as a function of time and reactor core life to accident.

Outflow of the radioactive substance outside the containment is feasible due to operation of the safety value and through the compartment vessel untightness, which may be the highest possible in operation at a rate of about 1.0% volumes per hour [11,12]. The physical and chemical characteristics of a radioactive cloud of the activity emission are formed under an influence of a number of factors which are random for the moment of release and can be attributed to the climatic and meteorological conditions of the ship's geographic position.

*Table 2.1.*

**Isotopic Composition of Primary Coolant inventory, %%**

| Fraction | Isotopes | Duration of reactor continuous operation, days | | | |
|---|---|---|---|---|---|
| | | 3 | 7 | 20 | 60** |
| gaseous<br>+<br>Daughter<br>products | Kr - 85 m | 5.65 | 3.64 | 2.36 | 1.89 |
| | Kr - 87 | 4.04 | 3.31 | 2.36 | 1.89 |
| | Kr - 88 | 12.54 | 9.92 | 6.64 | 4.74 |
| | Xe - 133 | 9.07 | 27.58 | 51.16 | 63.30 |
| | Xe - 135 | 40.66 | 34.19 | 22.57 | 16.63 |
| | Xe - 135 m | 3.95 | 2.54 | 1.72 | 1.33 |
| | Xe - 137 | 3.16 | 2.31 | 1.50 | 1.23 |
| | Xe - 138 | 5.08 | 3.97 | 3.00 | 2.45 |
| | Rb - 88*) | 11.30 | 8.93 | 5.90 | 4.29 |
| | Cs - 138*) | 4.52 | 3.61 | 2.79 | 2.25 |
| %% | | 100.0 | 100.0 | 100.0 | 100.0 |
| % in mixture | | 88.6 | 90.9 | 93.1 | 94.5 |
| Halogens<br>+<br>Caesium | Br - 83 | 1.68 | 2.51 | 1.89 | 1.83 |
| | Br - 84 | 2.58 | 2.51 | 2.52 | 2.56 |
| | Br - 85 | 1.25 | 1.00 | 0.92 | 0.97 |
| | J - 131 | 0.90 | 1.88 | 2.73 | 3.64 |
| | J - 132 | 5.56 | 5.01 | 3.78 | 3.64 |
| | J - 133 | 18.12 | 20.37 | 19.31 | 20.23 |
| | J - 134 | 27.19 | 26.64 | 27.29 | 26.15 |
| | J - 135 | 27.19 | 26.64 | 27.29 | 26.15 |
| | Cs - 139 | 15.53 | 13.44 | 14.27 | 14.83 |
| %% | | 100.0 | 100.0 | 100.0 | 100.0 |
| % in mixture | | 7.7 | 6.4 | 4.8 | 3.7 |
| Non-volatile | Sr (90-92)<br>J-92, La-141<br>Ba (139-141) | % in mixture | | | |
| | | 3.7 | 2.7 | 2.1 | 1.8 |

*) - daughter isotopes being at equilibrium with parent isotopes

**) - after 60 days of reactor operation the isotopic composition has remained practically unchanged.

*Table 2.2.*

**Exposure gamma-radiation dose rates on the cylindrical volume source axis (containment vessel), R/hr.**

| Reactor continuous operation time, days | Normalised initial activity, Ci/l | Time elapsed since accident, hr. | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | $1\,10^{-1}$ | $5\,10^{-1}$ | 1.0 | 5.0 | $1\,10^{1}$ | $5\,10^{1}$ | $1\,10^{2}$ |
| 7 | 0.1 | $5.5\cdot10^{2}$ | $3.8\cdot10^{2}$ | $3.3\cdot10^{2}$ | $1.3\cdot10^{2}$ | $7.0\cdot10^{1}$ | $9.0\cdot10^{-1}$ | $5.0\cdot10^{-2}$ |
| | 1.0 | $5.5\cdot10^{3}$ | $4.0\cdot10^{3}$ | $3.0\cdot10^{3}$ | $1.5\cdot10^{3}$ | $5.5\cdot10^{2}$ | $7.0\cdot10^{1}$ | $6.0\cdot10^{-1}$ |
| 20 | 0.1 | $4.0\cdot10^{2}$ | $2.4\cdot10^{2}$ | $1.8\cdot10^{2}$ | $4.8\cdot10^{1}$ | $1.6\cdot10^{1}$ | $6.0\cdot10^{-2}$ | $3.0\cdot10^{-3}$ |
| | 1.0 | $4.0\cdot10^{3}$ | $2.5\cdot10^{3}$ | $1.8\cdot10^{3}$ | $5.0\cdot10^{2}$ | $1.5\cdot10^{2}$ | $5.8\cdot10^{-1}$ | $3.1\cdot10^{-2}$ |
| 60 | 0.1 | $2.5\cdot10^{2}$ | $1.8\cdot10^{2}$ | $1.4\cdot10^{2}$ | $2.5\cdot10^{1}$ | $0.7\cdot10^{-1}$ | $2.0\cdot10^{-2}$ | $3.0\cdot10^{-3}$ |
| | 1.0 | $2.6\cdot10^{3}$ | $1.8\cdot10^{3}$ | $1.4\cdot10^{3}$ | $2.4\cdot10^{2}$ | $0.9\cdot10^{1}$ | $1.8\cdot10^{-1}$ | $2.9\cdot10^{-2}$ |

From the standpoint of environmental impact produced by the radioactive emissions two basic components may be identified:

- external irradiation of varying intensity induced by a cloud containing inert gases of krypton-xenon group, iodine as well as aerosol components of fuel compositions and corrosion products of the plant structural materials (depending on the meteorological condition for the moment of accident duration of this period can appreciably vary);
- internal alpha-beta irradiation of critical human organs induced by radioactive substances penetrated inside the organism basically through inhalation.

Duration of impact produced by the mentioned factors is dictated by a package of protective and preventive measures and depends on administrative decisions to confine the accident and eliminate the after-effects based on operative information on the characteristics of same.

Among such characteristics are:

- technical condition of the core for the moment of accident;
- duration of the reactor continuous operation;
- location and extent of the loss of leaktightness of the primary pressure boundary;
- emission or no-emission of radioactive substances outside the containment vessel.

The analysis of design basis accidents involving loss of leaktightness of the primary pressure boundary accompanied by outflow of the stream-and-air mixture to the space of the containment has shown that such an accident entails more severe after-effects as compared to possible leakage of the primary coolant into secondary or third circuits.

In assessing radiation after-effects of the loss of leaktightness of the primary pressure boundary the limiting value of the primary specific activity was taken to be $10^{-2}$ Ci/l which corresponds 0.1% open surface of the nuclear fuel. The entire gaseous fraction and iodine group were withdrawn to the space of the containment vessel.

In this case the total activity of the gaseous component of the mixture is $1 \cdot 10^4$ Ci while that of the iodine is 40 Ci and the initial levels of gamma-radiation (dose rates) induced by the volume source on the injured ship amount to: 250 to 470 μR/s on the reactor compartment bulkheads, 25 μR/s in the RCR, 70 μR/s in the cabins of the first superstructure tier, 250 μR/s in the engine room, 120 μR/s on the ship's side in way of the waterline.

It should be noted that owing to operation of the accident confinement systems activity of the radioactive source decreases within 12 hours by a range of two-three orders the integral irradiation doses within 24 hours in the RCR and crew cabins amount to about 0.2 rem and 0.4 rem, respectively.

Release of the activity into the atmosphere within the period of the emergency situation confinement amounts to $1 \cdot 10^4$ Ci with regard to the gaseous component and 40 Ci with regard to the iodine which can results in irradiation doses of 2 rem on board the icebreaker and of 1 to 100 mrem outside thereof, depending on the meteorological and climatic conditions.

2.2. It the primary pressure boundary suffers gas untightness within the high-pressure gas system about 250 Ci, basically: xenon - 133, leak into the containment. In such a case the levels of gamma-radiation in the RCR and on sides of ship do not exceed values in normal operation.

When primary coolant leaks into the secondary system the leaky steam generator is cut off with regard to steam and water. 500 Ci of iodine leak into the secondary system within the cut off time. These products are discharged into the atmosphere through the ventilation system. The integral equivalent doses amount to about 1 rem in the RCR, up to 1 rem in the engine room, 0.5 rem on the sides and 1 mrem outside the icebreaker.

If the primary coolant leaks into the third coolant system within the time the leaky section of heat exchanger was cut off (0.5 hr) the gaseous and iodine components of respectively 1500 Ci and 300 Ci enter into an expansion tank.

Iodine and non-volatile fractions are confined within the volume of the third circuit water. In this version, the integral irradiation doses do not exceed 0.4 rem for the crew and 0.05 rem for the public owing to gradual emission into atmosphere of 1100 Ci gaseous component and 10 Ci iodine.

In examining versions of the loss of leaktightness of the primary pressure boundary in the nuclear icebreaker reactors a conservative approach to assess the radiation after-effects of the accident has been adopted.

In all the examined cases the primary pressure boundary suffered loss of leaktightness the radiation situation on board and around the ship poses no hazard to the crew, ships in the convoy, environment and public.

# 3. ANALYSIS OF NAVIGATIONAL ACCIDENTS

## 3.1. Nuclear icebreaker-to-ship collision.

Using statistical data a study of the size and speed of commercial ship throughout the world was carried out, the risk of the ship damaged by a collision at critical speed should that possibility of this occurring was only 2.3%. Considering that the colliding ship is not always at full load and further that the mean colliding angle is 70° and a deceleration of 1 knot is expected immediately before collision, the possibility was only ~0.5% [13].

An analysis of the navigational accidents in the international shipping shows that the damage risk for the nuclear power plant on a ship provided with collision protective structure which absorbs the entire collision kinetic energy is rather slight.

When two ships collide their interaction is of inelastic nature with impact acceleration not exceeding 1 g.

The plants of the Russian nuclear icebreakers have be so designed and constructed that the reactor and associated equipment remain operable at impact loads of no less than 3 g in any direction (vertical and horizontal component).

Provision of collision protective structure in way of the reactor compartment rules essentially out, when a collision occurs, the possibility of damaging hull in this area to a depth exceeding 0,2 of the ship's breadth and this does not result in damage to the plant-related equipment. An accident involving breakdown and flooding of the reactor compartment may be considered as hypothetical and is not dealt with in this work.

In case where the nuclear icebreaker collides with another ship or a stationary object an emergency reactor shut-down is effected and necessary action is initiated to remove residual heat from the core with the use of the main or ancillary cooling systems. The radiation conditions on board and around the ship remain unchanged.

## 3.2. Stranding of the nuclear icebreaker.

The impact loads applied to the reactor plant when the ship runs aground are lower than those resulting from collision. The action to be taken by the personnel is similar to that in case of collision.

In analysing the radiation consequences of an accident it is assumed that the ship sinks down to the upper deck, on even keel, and sea water tills the reactor and engine compartments. The main and stand-by electric power supply systems become in this case inoperable. From a loss of power signal the reactor emergency protection comes into action, all the emergency control rod groups and reactivity control rod groups lower mechanically onto the lower limit switches. As a result, the reactor is rendered sub-critical (shutdown). Within 10 to 16 sec. of the loss of power emergency diesel-driven generators and emergency feedwater pumps are started to provide residualheat removal from the core.

When the pressure in the steam generators has reached 10 kg/sq.cm feed water is supplied thereto at a flow rate 15 cu.m/hr. Feed water capacity is 100 t. Steam is dumped through the waste steam pipe line at a flow rate of 15 t/hr.

Because of the fact that the primary pressure boundary retains its leaktightness the radioactivity does not release outside thereof.

When the icebreaker runs aground particular attention is drawn to the possibility of sea water supply to ensure the residualheat removal from the core. When it is impossible to supply sea water to forth cooling circuit (tidal phenomena exist) replenishable water supply from the ballast tanks is used. In this case the radiation conditions on board and in the vicinity of the ship do not get worse as well.

## 3.3. Sinking of the nuclear icebreaker.

Sinking of the nuclear icebreaker with undamaged reactor plant and containment takes at varying sinking velocity depending on damage mode as the spaces are flooded. Emergency reactor shutdown is effected and action is initiated to cool the plant as long as it is possible based on the crew safeguarding conditions.

An analysis of radiation consequences of ship sinking in shallow water has been made proceeding from the following initial provisions:

- fission - fragment coolant activity for the moment of sinking amounts to $3.7 \cdot 10^{-2}$ Ci/l;
- reactor core and vessel have not been destroyed;
- radioactive products emanating from the primary system, as elements of the latter are destroyed, will be confined within the containment volume;
- flooding of the containment by sea water through the flooding valves begins from the depth of 5 m until the depth of 80 m has been reached (depth of closing the flooding valves).

Thermotechnical characteristics of the primary coolant system when the containment has been flooded are given in Fig. 3.1 and 3.2 from which it is seen that the temperature and pressure within the primary coolant system, after reaching the maximum value, then drop smoothly. The limiting values of the coolant parameters remain below the critical ones , hence the primary pressure boundary is not destroyed.

When the sunken icebreaker lies in water the primary pressure boundary will be depressurised due to corrosion processes with resulting release of the nuclear fuel fission products into the containment space. Table 3.1 gives depressurisation points of the primary pressure boundary due to failure of the equipment under the action of external pressure.

Fig.3.I. Variation of the coolant parameters with time $\tau$, s when the icebreaker sank in shallow water

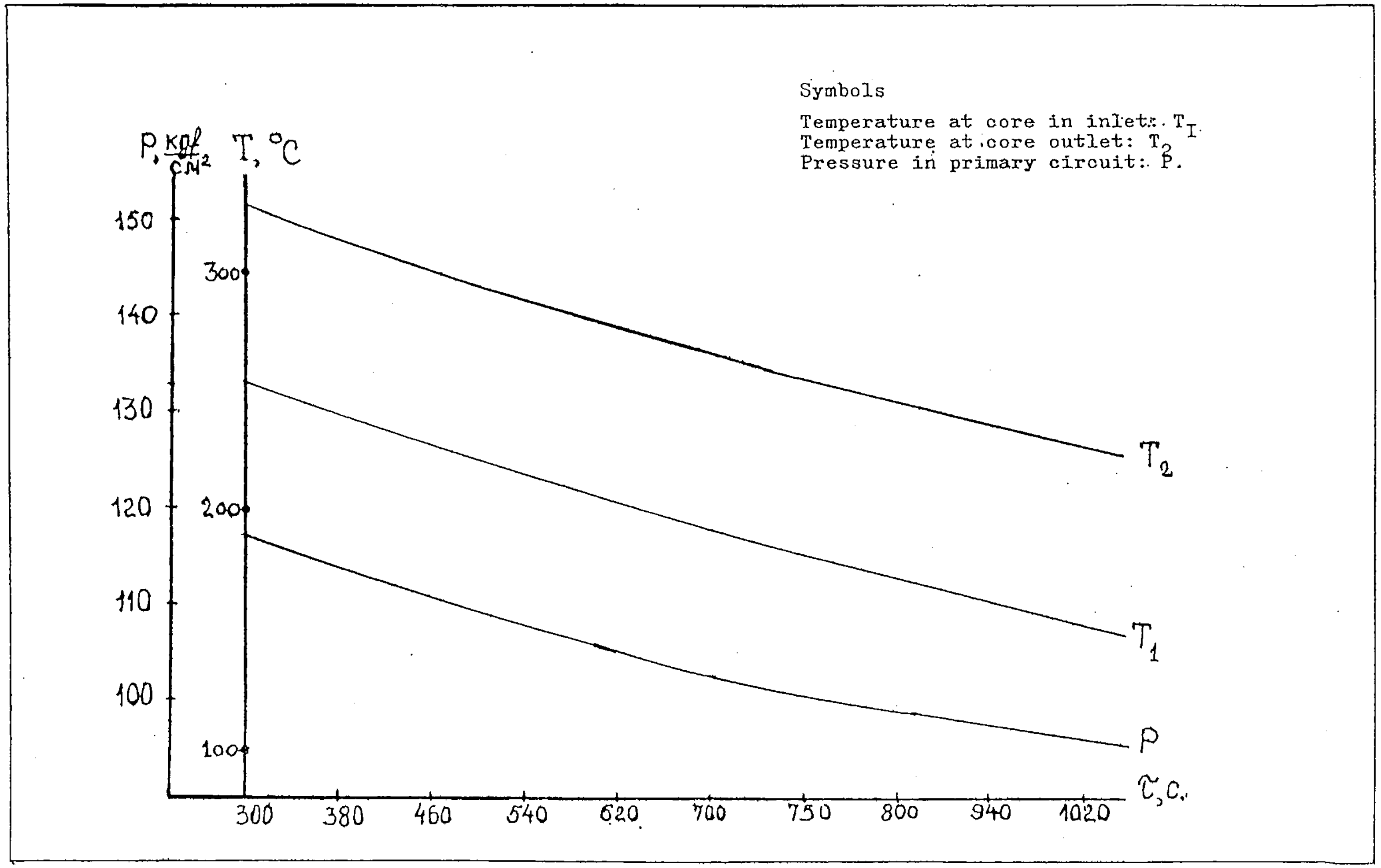

Fig.3.2. Variation of the coolant parameters with time $\tau$, s when the icebreaker sank in deep water

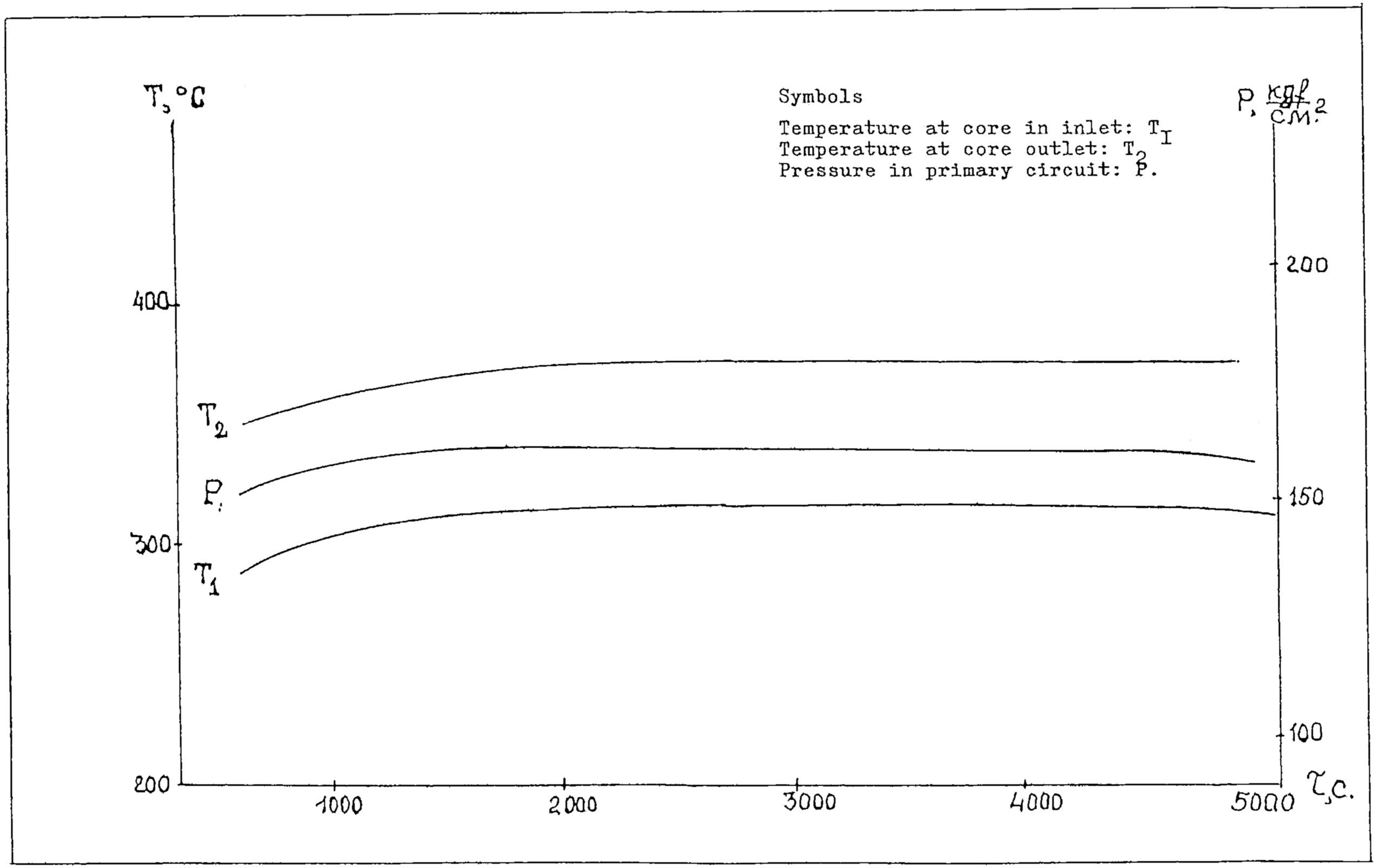

*Table 3.1.*

**Depressurisation of the primary pressure boundary due to destroy of the equipment under the action of external pressure.**

| Equipment of the primary pressure boundary | Depth at which the icebreaker sank, m | Critical external pressure, kgf/sq.cm | Time elapsed from the moment of sinking until destroy, s |
|---|---|---|---|
| Reactor | 10000 | 10000 to 1670 | abt. 1200 |
| Steam generator | 3000 to 9000 | 300 to 900 | 400 to 1100 |
| Primary circulating pump | 4000 to 6500 | 400 to 700 | 400 to 700 |
| Emergency protection and reactivity control drives | 1600 to 5000 | 160 to 530 | 220 to 650 |
| System pipe lines, fittings | 2400 to 1000 | 246 to 10000 | 300 to 1000 |

Depressurisation of the primary pressure boundary due to corrosion processes in sea water proceeds more slowly and takes years (from 1.5 up to 100 years and more) depending on the mass characteristics of the reactor equipment.

As the temperatures and pressures within the primary pressure boundary are equalised to surrounding water the corrosion destruction process of fuel composition is initiated. This process is responsible for constant velocity of the activity release into the containment space. Subsequent release of the radioactive products and carry-over of same in aquatic environment are governed by hydrological characteristics of the sink site. Simulation of the radioactive substance migration, acceptable for practice activity (energy carrier extraction, fishery, hunting, seafaring etc.) is possible based on an analysis of full-scale measuring to parameters of models simulating environmental exchange and effect produced by the physical and chemical, hydrological and weather factors on such a process.

Because of the fact that sinking in deep water of an icebreaker on the Arctic Sea routes is highly improbable then for further analysis of the radiation effect a case of radioactive substance release caused by corrosion process will be assumed.

Distances to which the radiation effect (in acceptable concentrations) of the accident involving ship sinking extends are given in Table 3.2 at current velocities of 0.04 and 4 m/s for a number of long-lived isotopes.

*Table 3.2.*

**Water area contamination in acceptable concentration resulting from the corrosion process phase, m**

| Isotope | Current velocity, m/s | Release time, hr. | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 5 | 10 |
| Strontium-90 | 0.04 | 3047 | 3011 | 2902 | 2733 |
| | 0.40 | 9635 | 9528 | 9177 | 8641 |
| Ruthenium-106 | 0.04 | 108 | 290 | 103 | 18 |
| | 0.40 | 1292 | 916 | 326 | 58 |
| Cesium-137 | 0.04 | 484 | 477 | 460 | 435 |
| | 0.40 | 1525 | 1507 | 1456 | 1375 |
| Cerium-144 | 0.04 | 1550 | 993 | 261 | 28 |
| | 0.40 | 4900 | 3140 | 826 | 89 |

The vertical and transverse (perpendicular to the current velocity vector) dimensions of the spot are:

vertical: 1570 m at current velocity of 0. 04 m/s and
279 m at current velocity of 0. 40 m/s.

transverse: 19. 4 m and 10. 9 m at current velocity of 0. 04 and 0. 40 m/s, respectively.

It was assumed in the process of analysis that 10% of the fuel composition area is in contact with sea water and in this case Strontium-90: $2.25 \cdot 10^3$ Ci, Ruthenium-106: $7.02 \cdot 10^2$ Ci, Cesium-137: $1.82 \cdot 10^4$ Ci and Cerium-144: $1.24 \cdot 10^3$ Ci ingress into the containment space.

Thus, when a nuclear icebreaker sinks on the Arctic Sea routes radioactive contamination of the water area is of local nature, which hazard to the anthropological activity can be reduced to a minimum impact with the use of organisational and technical arrangements of control and restrictive nature.

Assessments displayed above have been made with the use of a methodical approach to generation of models simulating activity carry-over in an aquatic environment quoted in research work: "Development of an Automated Radiation Monitoring System ...".

### 3.4. Fire on the nuclear icebreaker.

Fire protection of power plant compartments on the nuclear icebreaker is insured by active facilities and appropriate structural arrangements.

The most severe type of fire on board is that which involves heat-up of the high-pressure gas receiver bottles in the equipment room within containment. The results of an analysis made for the icebreakers as "Rossia" and "Taimyr" type show that when heat releases into the containment space at $3.6 \cdot 10^6$ kJ within two hours the bottles are heated up to 100°C, gas pressure at that time mounts up to 230 kgf/sq.cm.

The limiting pressure in the high-pressure gas system at fire temperature amounts to 230 kgf/sq.cm while the pressure defining the bottle destruction limit is 450 kgf/sq.cm. Thus, a fire will not entail destruction of the high-pressure gas system, hence the primary pressure boundary will remain intact. Actions of the crew under such conditions are set forth in the "Damage Control Manual", Section "Fire On Board an Icebreaker".

3.5. A fire in the main reactor control room or engine room signifies that control of the plant from these positions become impracticable. From a signal "Fire in MRCR (Engine Room)" the personnel on watch on the navigating bridge undertakes dropping of the emergency and reactivity control rods, supervision over position of same in the core and start of the emergency electrical power sources residualheat is removed from the separate emergency reactor control position, primary system pressure and temperature as well as coolant level in pressuriser being monitored.

When the above actions are taken to remove residualheat from the core no tightness of the primary pressure boundary is lost and the radiation conditions on board and around the icebreaker remains the limits of safety standards.

# CONCLUSION

1. The nuclear propulsion plant of the "Rossia" and "Taimyr" type modern nuclear icebreakers used in the Arctic have been built to meet the requirements of national and international regularity documents as applied to the nuclear and radiation safety of this class of seagoing ships.

An analysis of emergency situations, though hardly probable but feasible (design basis), shows that safety of the icebreaker, environment and public is ensured to a rather great extent.

**Reliability Criteria of NPPs of "Arctica"-type Icebreakers**

| Criteria | NPP | Component Systems | | |
|---|---|---|---|---|
| | | NSSS | STS | EPS |
| Mean time to emergency stop at sea, $1 \cdot 10^3$, 1/h | 3.4 | 0.2 | 1.4 | 1.5 |
| Mean recovery time, $1 \cdot 10^2$, 1/h | 35.7 | 22.2 | 45.5 | 26.3 |

Not a single emergency case resulted in an aggravated radiation situation onboard or to personnel radiation overdosing. In this case all risk has only navigational character. This risk is not a corollary of deterioration of radiation situation.

2. The results of the analysis of effect produced by the nuclear icebreakers on ecology of the Arctic basin show that use of same for the purposes of international shipping does not affect adversely the environment of the region.

3. Provision of LCN on board the nuclear icebreakers to generate data bank on technical condition of the reactor-related equipment and safety systems makes it possible to make prompt assessment and predict development of the radiation situation on board and outside the ship in normal and extreme conditions of sailing in conjunction with other ships of the convoy.

To enter into the information system provided for in INSROP studies should be made in co-operation with the contractors of the INSROP information subsystems*) to develop entry protocols of information subsystems based on unified standards of the facilities used, geographic maps, coded reports of radiation situation in normal and emergency conditions of using the nuclear icebreakers in international shipping in the Arctic.

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*) Sub-Programme 1: Natural Conditions and Ice Navigation
1.2.1 - Operational Information and natural conditions.

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# Environmental Safety of Nuclear Icebreakers, Part II

# LIST OF ABBREVIATIONS

SS - Scram System
EFP - Emergency Feed Pump
NES - Nuclear Engineering Support
MMARMS - Merchant Marine Automated Radiation Monitoring System
INSROP - International Northern Sea Route Programme
LCN - Local Computer Network
SG - Steam Generator
GD - Guidance Document
PCP - Primary Circulating Pump
CCR - Central Control Room
NSSS - Nuclear Steam Supply System
NPP - Nuclear Power Plant
CRCRG - Central Reactivity Control Rod Group
FA - Fuel Assembly
WSS - Warning Signal System
ASS - Alarm Signal System
SDG - Stand-by Diesel-Generator
EDG - Emergency Diesel-Generator
RCG - Reactivity Control Rod Group
ECT - Emergency Cooling Tank
SSCR - Self-Sustaining Chain Reaction
EDR - Exposure Dosage Rate
CMS - Centralised Monitoring System
NSR - Northern Sea Route
MFSS - Manual on Fighting for Survivability of Ships
USARMS - Unified State Automated Radiation Monitoring System

## INTRODUCTION

1. There are accidents not contemplated by the technical and service documentation, caused by initial events neglected for the design-based accidents or followed by additional (as compared to the design-based) failures of the safety in excess of a single failure as well as by implementation of wrong solutions (actions) of the personnel which can result in heavy damages and (or) fusion of the core, which consequences can be mitigated by accident control and (or) implementation of arrangements to protect the personnel and population.

2. The experience gained in safe operation of the Russian Nuclear Fleet shows high reliability of the used marine nuclear power plants as well as the fact that the probability of the non-design-based accidents is very slight but cannot be reduced to zero.

### *To estimate the risk for environment in case of non-design-based accident*

Many years experience of the ship NPPs plants confirmed their high reliability and safety. The probability of fail-safe NPP operation is in the range of 0.97 - 0.99 for the period of continuous operation during 5000 hours. On the basis of the analysis of the safety systems' structural reliability the values of the coefficients of operational non-availability are in the range $10^{-2}$ - $10^{-3}$. Taking into account that the probability of emergency situations which require the operation of safety systems does not exceed $10^{-2}$ - $10^{-3}$ during continuous operation, the probability of the accident's realisation is not higher than $10^{-5}$ - $10^{-6}$, which allows to make a conclusion about the safety of NPP with water cooled and water moderated reactors [9].

Render the conditions where an emergency situation is likely to occur for the purpose of lessening the risk of radiation impact produced by the non-design-based accident on the ecological systems of the Northern Sea Route and the population of regions adjoining the latter the Shipowner's Administration Schedules and implements a package of accident prevention measures to ensure appropriate readiness in case where such an accident occurs.

Decision making concerning the need for implementation of measures commensurable with the accident to protect the personnel, population and environment is a logical conclusion of the process of overall evaluating the radiological consequences of the accident. Such an evaluation is based on prognostic calculations and current data and consists of individual information blocks of radiation and non-radiation nature.

3. The process of decision making managerial is based: on a fairly full volume of prognostic and live information on the nature and consequences of a plant accident for the nuclear ship and environment; on evaluation of the degree of radiation hazard in the temporal, spatial and population aspects; on evaluation of the expected completeness and efficiency of the recommended protective measures in correlation with the required expenditures for implementation thereof, extent of risk for the personnel and population.

Subject to consideration at the stage of preliminary prediction of the consequences of a non-design based accident occurred in the power plant of a nuclear ship are both the evaluations of technical condition in time and the factors of climatic, hydrological and meteorological nature affecting the scale and characteristics of its consequences.

4. Control of a non-design-based accident is aimed at returning the nuclear power plant in the controlled status at which the reactor is rendered sub-critical, providing fuel cooling and containing radioactive products within prescribed boundaries and quantities. A preliminary analysis of the plant conditions, development of managerial measures and training of the operating personnel for actions under the accidental conditions are prevailing to prevent the accident and mitigate the after-effects thereof. And in so doing, achievement of the previously specified objectives to ensure safety for each level of the plant emergency condition shall provide the basis.

For the plants used on board the Russian nuclear ships, among the typical levels of the plant emergency conditions may be :

- accidents involving faults in the systems of heat removal from the reactor core;
- reactivity-related accidents;
- accidents involving depressurisation of the primary pressure boundary with full or partial loss of coolant.

The physical and chemical characteristic of the radiation impact on environment are generated under the effect of a number of occasional (at the moment of accident) factors caused by the climatic and hydrometeorological conditions of the ship's geographic position.

From the standpoint of impact produced by the radiation factor on the population and ecological systems the following components shall be highlighted:

- external irradiation (beta-gamma components) of varying intensity from a plume containing radioactive inert gas of krypton and xenon group, iodine, aerosol fraction of fuel compositions and structural materials of the reactor cores, as well as from the underlying surface contaminated with radioactive substances. Depending of the hydrometeorological conditions of the region at the moment of accident duration of this period may vary considerably;
- internal irradiation (alpha-beta components) of the critical organs of people and animals from the radioactive substances incoming through the food chains and by inhalation inside the organism.

Duration of exposure to the said factors is dictated by the use of protective and preventive measures which defend on implementation of the managerial decisions taken to confine the accident and lower the level of its impact.

5. Development of the Local Computer Networks (LCN) based on modern computing facilities fitted on board the nuclear ships makes it possible to make continuous system and structures, take account of the resource characteristics. Work are being performed on board the Russian nuclear ships aimed at setting up closed information subsystems: ship-shore-ship with the use of shipboard and shore-based LCN and radio aids.

Existence of such an Information System enables:

- continuous and operational multikind monitoring of radiation conditions on board the

nuclear ship and in the nearest neighbourhood;
- reliable establishing the fact of radiation accident or failure of the radiation object;
- identification and evaluation of the nature, scale and prediction of the accident consequences;
- finalisation and correction of preliminary evaluation of the radiation conditions through making actual measurements and analysis of air and aquatic environment samples;
- information exchange between structural blocks of the System;
- extension of the Information System through adding the chemical and bacteriological sub-systems (if necessary).

The ships of the convoy escorted by a nuclear icebreaker in the Arctic shall be provided with the information system terminals which will make it possible to implement emergency arrangements with regard to and in the interests of all the ships of convoy.

The INSROP Project contemplates creation of an Information System which would make it possible to carry out operational control with regard to various navigational conditions in the Arctic Basin. This System shall incorporate an information sub-system to make managerial decisions in case of an improbable but theoretically non-ignorable non-design based accident of a nuclear plant. In so doing in collaboration with the authors of various sub-systems of the project: studies of interface protocols of the information, unified standards of geographical maps, coded messages, hardware complex shall be made.

# 1. ANALYSIS OF ACCIDENTS INVOLVING THE NUCLEAR POWER PLANT MALFUNCTIONS.

In case of an accident the thermotechnical characteristics of the core change significantly with the resulting pressure rise in the primary circuit up to the limiting values, disablement of the plant with possible loss of leak tightness of the equipment.

Under these conditions the prime object is to reveal time reserve available for the operating personnel and the crew of the ship suffering average after completion of automatic operations by the complex of the plant technical facilities control systems.

As an initial condition of the NSSS preceding the accident it is taken that the plant has been running at rated power for some 20 hours at continuous operation of the reactor within 8000 hours at an average power of 40% of the rated value.

In view of the fact that on board the Russian nuclear ships throughout the period of their use there were no situations caused by the non-design-based accidents evaluation of the post-emergency condition is made on the basis of the operating experience and design and service documentation of the operational marine power plants. Thermotechnical reliability of the reactor core in these plants is provided by crisisless operating mode of the core channels and this ensures thermotechnical reliability of the core, conservation of its resource characteristics.

1.1. In case where a crisis of heat exchange occurs and develops in a portion of the fuel assemblies a steady heat exchange is maintained for some time and the latter ensures a relatively slow temperature rise in fuel claddings. The temperature of the core claddings in the neighbourhood of $600^{0}$ C defines temperature boundary of the plant safety limit , when the above values are exceeded the fuel assembly begins to break down.

The safety limits based on the strength conditions of constructional materials of the NSSS primary circuit equipment are defined by:

- limiting pressure which being not exceeded is sufficient to maintain functioning of power-generating equipment, which is assured by 20% safety factor based on stress ($P_1$~21-22 MPa);
- lower pressure limit at which plastic deformation of the constructional material is achieved in the weakest element of the equipment ($P_2$~30-40 MPa);
- limiting value which been exceeded results in destruction of the weakest element of the equipment ($P_3$~45 MPa).

1.2. Accidents involving unauthorised power increase reactivity type is develop into the non-design-based ones, in contrast to the design-based accidents discussed in [1], follow a more severe scenario and, as a rule, result in the core overheat threat and loss leak tightness of the primary circuit equipment.

When analysing accidents involving depressurisation of the primary pressure boundary with complete failure of the emergency core cooling systems and drainage of the core the crucial factor is the thermal resistance of the elements.

The criteria of radiation safety involving fusion of the core are in this case:
- radiation situation in the spaces of the ship in an emergency;
- radiation situation the surrounding waters;
- condition for containment of melt of the assemblies and core constructional materials within the reactor ship.

The results of the analysis of emergency situations, initial event versions in conjunction with probable failures in safety systems that result in possible accidents of the NSSS are given in Table 1.1.

1.3. The mechanism of releasing the steam and air mixture, the physical and chemical characteristics of the latter are given in [1]. Migration of the fission products from the zone of nuclear fuel fusion is defined by the diffusion coefficients of the mixture components and amounts to about $10^{-5}$ cm/sec for inert gas, halogens and alkali components. The majority of metals form non-volatile, high-melting ruthenium oxides.

Up to 90% of inert gas and halogens, 80% of alkali metals (caesium and rubidium), 15% of tellurium, selenium and antimony, strontium, barium and 10% of ruthenium oxides pass outside the primary circuit. [2].

Due to temperature difference between the steam and air mixture and compartment structures, physical and chemical properties of the elements concentration of the radioactive products of the mixture drops owing to precipitation and sorption processes.

For the inert gas the coefficient of sorption is nil, for the iodine and caesium: $2x10^{-3}$-$5x10^{-2}$ which corresponds to elimination constant of $8x10^{-5}$ $sec^{-1}$ [2].

One of the unfavourable factors of the accident involving fuel fusion is the probability of a spontaneous chain reaction to be occurred in the melt, this accident being accompanied by destruction of the plant and ship's structures. In this case the isotopic composition of the mixture's fission products includes also so called "hot particles" generated from the dispersed nuclear fuel and constructional materials of the core. The isotopic composition and specific activity of the "hot particles" is given in Table 1.2.

1.4. Evaluations of radiation impact of the accidents involving disturbance of the NSSS protective barriers for emergency situations discussed in Section 2 - "Loss of Leak Tightness of the NSSS Primary Circuit" and Section 3 - "Analysis of Navigational Accidents" of report [1] have been made using a similar approach to description of the radioactive product carry-over process.

1.4.1. An accident involving initiation of the SCR on the plant, resulting in release of a radioactive cloud into the surrounding space to a height up to 200 m. Evaluation made for unsteady state of the atmosphere and wind speed up to 5 m/s is given in Table 1.3.

**Table 1.1. Analysis of Possible Consequences of Possible Initial Events of Development of Emergency Situations**

| Emergency Situation | Initial Events in Combination with Failures in Safety Systems | Possible Sequences |
|---|---|---|
| 1 | 2 | 3 |
| 1. Unauthorised increase of the NSSS power (positive reactivity insertion) | 1.1. Closing of feed and throttle valves with emergency rate;<br>failure in operation of warning and alarm signal system when appropriate power settings are exceeded. | Core overheat threat (temperature of fuel elements claddings in some FA amounts up to 500°C to 550°C);<br>time for reaching critical parameters is 30 to 35 s. |
| | 1.2. Withdrawal of CRCRG with normal Rate when reactor is started up;<br>failure in operation of warning and alarm signal system according to power doubling period reduction settings in combination with failure in actuation of warning and alarm signals according to power level overshoot settings (starting and power-generating ranges). | Core overheat threat (temperature of fuel claddings in some FA amounts up to 500°C to 550°C) and loss of leak tightness (pressure in transient process amounts up to 29 MPa);<br>time for reaching critical parameters is 60 s. |
| | 1.3. Unauthorised withdrawal of CRCRG with emergency rate (25 mm/s) when reactor in started up (only with "Mars" type system) and in the absence of other failures. | Core destruction threat (fuel temperature exceeds 1500°C);<br>time for reaching critical parameters is 5 to 10 s. |
| | 1.4. Unauthorised withdrawal of CRCRG with normal rate during NSSS power operation in combination with failures in actuation of warning and alarm signals. | Threat of core destruction and loss of leak tightness of primary circuit equipment;<br>time for reaching critical parameters is more than 60 s. |
| | 1.5. Unauthorised withdrawal of CRCRG with emergency rate during NSSS power operation (only with | Threat of core destruction and loss of leak tightness of primary circuit equipment;<br>time for reaching critical |

| Emergency Situation | Initial Events in Combination with Failures in Safety Systems | Possible Sequences |
|---|---|---|
| 1 | 2 | 3 |
|  | "Mars" type system) in combination with failures in actuation of warning and alarm signals. | parameters is 2 to 7 s. |
| 2. Disturbance in heat removal from reactor core. | 2.1. Failure of feed water supply to SG in combination with failures of water supply by means of EFP and additional failures: | Subsequent to SS operation due to inadequate heat removal from reactor core temperature and pressure rise within prime circuit. |
|  | 2.1.1. Filter cooler has been not switched in cooling mode but remained switched in clean-up mode. | Maximum pressure value in primary circuit does not exceed limiting values.<br>Reliability of reactor core is assured. |
|  | 2.1.2. Filter cooler has been switched in cooling mode; two PCP have been started up at low speed. | Maximum pressure value within primary circuit does not exceed limiting values (amounts up to 17.2 MPa).<br>Reliability of reactor core is assured. |
|  | 2.1.3. Filter cooler has been not switched in cooling mode; clean-up system was taken out of service; cooling system (third circuit) is in operation. | Pressure within primary circuit reaches critical values corresponding to $P_1$ value within 1.33 hr.<br>Pressure level $P_2$ is reached within 4 hr.<br>Pressure level $P_3$ is not reached.<br>Reliability of reactor core is assured. |
|  | 2.2. Complete loss of electrical power supply to NSSS services in Combination with failure in SDG and EDG starting subsequent to SS actuation and impossibility of putting them into operation; sticking of all or part of RCRG in combination with additional failures: | Lacking heat removal from reactor core upon SS actuation pressure and temperature within primary circuit rise; reliability of reactor core is assured. |

| Emergency Situation | Initial Events in Combination with Failures in Safety Systems | Possible Sequences |
|---|---|---|
| 1 | 2 | 3 |
| | 2.2.1. Disconnection or absence of ECT, failure in actuation of automatic safety device of primary circuit over pressurisation protection system. | Maximum pressure value within primary circuit is determined by time during which heat removal from reactor core is organised. Lacking heat removal, time for reaching critical pressure values corresponding to $P_1$, $P_2$, $P_3$ levels amount to 0.835 hr, 1.45 hr, 2.5 hr. |
| | 2.3. Failure of heat removal to sea water during falling tides in case of standing. | After scheduled throw-down of emergency control rods when cooling is properly organised primary circuit parameters are maintained below specified safety levels. |
| | 2.3.1. Stranding of ship with periodic supply of sea water to cooling system being retained (interruption of sea water supply 2 times per day for 2 to 4 hr). | |
| | 2.3.2. Stranding of ship with a heel in excess of 22.5°. Electrical power generating plant and safety systems remain to be operable. | |
| | 2.3.3. Stranding of ship with a heel in excess of 22.5°. Failure of electric power sources and safety systems in likely to occur. | After throw-down of emergency control rods at the time of complete loss of electrical power pressure and temperature within primary circuit rise due to lack of heat removal from reactor core; reliability of reactor core is assured.<br>Pressure within primary circuit amounts up to critical values corresponding to $P_1$, $P_2$, $P_3$ |

| Emergency Situation | Initial Events in Combination with Failures in Safety Systems | Possible Sequences |
|---|---|---|
| 1 | 2 | 3 |
| | | levels for NSSS of icebreakers within 1.15 hr, 2.45 hr, 4.03 hr. |
| 3. Depressurisation of primary pressure boundary. | 3.1. Gas or minor replenishable leak of primary system. | Threat of development of minor leak into major one with consequences specific thereto. |
| | 3.2. Major non-replenishable, non-interceptable leaks of pipelines and equipment of primary system into reactor space or equipment room; leaks from primary to secondary circuits (rupture of steam header of pipe system in full section) and to third circuit (rupture of tube of PCP filter or cooler in full section) in combination with various failures in automatic actuation of safety system fittings including core cooling system, starting of machinery and sets. | Threat of core drainage, complete or partial fusion thereof; hazard of releasing radioactivity into environment. |

**Table 1.2.** **Isotopic Composition and Specific Activity of the Components of Hot Particles [2].**

| Component | Specific Activity, Ci (Bk)/g | Component | Specific Activity, Ci (Bk)/g |
|---|---|---|---|
| Strontium - 89 | 0.48 $(1.3 \cdot 10^{10})$ | Cerium - 144 | 0.59 $(2.2 \cdot 10^{10})$ |
| Strontium - 90 | 0.03 $(1.2 \cdot 10^{9})$ | Europium - 154 | $1.24 \cdot 10^{-3}$ $(4.6 \cdot 10^{7})$ |
| Zirconium - 90 | 0.81 $(3.0 \cdot 10^{10})$ | Neptunium - 239 | 2.98 $(1.1 \cdot 10^{11})$ |
| Niobium - 95 | 0.78 $(2.9 \cdot 10^{10})$ | Plutonium - 238 | $1.16 \cdot 10^{-4}$ $(4.3 \cdot 10^{6})$ |
| Ruthenium - 103 | 0.67 $(2.5 \cdot 10^{10})$ | Plutonium - 239 | $1.27 \cdot 10^{-4}$ $(4.7 \cdot 10^{6})$ |
| Ruthenium - 106 | 0.02 $(6.6 \cdot 10^{9})$ | Plutonium - 240 | $1.62 \cdot 10^{-4}$ $(9.7 \cdot 10^{6})$ |
| Iodine - 131 | 0.35 $(1.3 \cdot 10^{10})$ | Plutonium - 241 | $2.97 \cdot 10^{-5}$ $(8.3 \cdot 10^{5})$ |
| Tellurium - 132 | 0.30 $(1.1 \cdot 10^{10})$ | Plutonium - 242 | $3.51 \cdot 10^{-7}$ $(1.3 \cdot 10^{4})$ |
| Caesium - 134 | 0.35 $(1.3 \cdot 10^{10})$ | Americium - 241 | $2.24 \cdot 10^{-5}$ $(8.3 \cdot 10^{5})$ |
| Caesium - 137 | $2.2 \cdot 10^{-2}$ $(8.4 \cdot 10^{8})$ | Curium - 242 | $5.13 \cdot 10^{-3}$ $(1.9 \cdot 10^{8})$ |
| Barium - 140 | 0.54 $(2.0 \cdot 10^{10})$ | Curium - 244 | $2.59 \cdot 10^{-5}$ $(9.6 \cdot 10^{5})$ |

**Table 1.3**

| Distance from the ship in an emergency along the wind direction, km | EDR from passing cloud, (R/hr) / (R/sec) | EDR from contaminated underlying surface, (R/hr) / (R/sec) |
|---|---|---|
| 0.2 | 1440 / 0.4 | 2.4 / $6.6 \cdot 10^{-4}$ |
| 0.4 | 18000 / 5.0 | 7.6 / $2.1 \cdot 10^{-3}$ |
| 0.6 | 24840 / 6.9 | 15.8 / $4.4 \cdot 10^{-3}$ |
| 0.8 | 22320 / 6.2 | 12.6 / $3.5 \cdot 10^{-3}$ |
| 1.0 | 16920 / 4.7 | 9.4 / $2.6 \cdot 10^{-3}$ |
| 2.0 | 7560 / 2.1 | 3.2 / $9.0 \cdot 10^{-4}$ |
| 4.0 | 2880 / 0.8 | 0.9 / $2.6 \cdot 10^{-4}$ |
| 10.0 | 720 / 1.2 | 0.14 / $4.0 \cdot 10^{-5}$ |

1.4.2. An accident involving sinking of the ship resulting in contamination of water area up to allowable concentrations of the most significant isotopes given in Table 1.4.

**Table 1.4**

| **Radioisotope** | **Half-life** | **Allowable concentrations in water** | |
|---|---|---|---|
| | | **Ci / cu.m** | **Bk / cu.m** |
| Strontium - 90 | 28.6 years | $4.0 \cdot 10^{-7}$ | $1.48 \cdot 10^{4}$ |
| Ruthenium - 106 | 368 days | $1.2 \cdot 10^{-5}$ | $4.50 \cdot 10^{5}$ |
| Caesium - 137 | 30.17 years | $1.5 \cdot 10^{-5}$ | $5.60 \cdot 10^{5}$ |
| Cerium - 144 | 284.3 days | $1.2 \cdot 10^{-5}$ | $4.50 \cdot 10^{5}$ |

Evaluation made for current speeds w at the site of sinking, which are 0.04 and 0.4 m/sec, is given in Table 1.5 for the case of 100% fusion of the nuclear fuel.

**Table 1.5**

| **Isotope** | **x, km** | | **a** | **b** |
|---|---|---|---|---|
| | **W = 0.04 m/s** | **w = 0.4 m/s** | **m** | **m** |
| Strontium - 90 | 19.5 | 195 | 50.3 | 27.3 |
| Ruthenium - 106 | 12.6 | 126 | 40.4 | 14.1 |
| Caesium - 137 | 20.6 | 206 | 51.8 | 29.7 |
| Cerium - 144 | 28.0 | 280 | 60.4 | 47.0 |

Here: x is the distance along the current axis, km;
a is the vertical dimension of an ellipse-shaped spot;
b is the transverse dimension of an ellipse-shaped spot.

Evaluation of the water area contamination depending upon the factor of corrosive washing out the radioactive products of the sunken affected ship is given in Table 1.6.

**Table 1.6**

| Isotope | Current Speed, m/s | Release time, years | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 5 | 10 |
| | | Distance along the current axis, m | | | |
| Strontium - 90 | 0.04 | 2904 | 2869 | 2769 | 2605 |
| | 0.4 | 9185 | 9074 | 8757 | 8239 |
| Ruthenium - 106 | 0.04 | 403 | 286 | 102 | 18.3 |
| | 0.4 | 1274 | 903 | 321 | 58 |
| Caesium - 137 | 0.04 | 225 | 223 | 214 | 203 |
| | 0.4 | 611 | 704 | 678 | 641 |
| Cerium - 144 | 0.04 | 1550 | 993 | 261 | 28 |
| | 0.4 | 4900 | 3140 | 826 | 89 |

Here:
The transverse and vertical dimensions of the ellipse-shaped spot:
at current speed 0.04 m/s
a = 1570 m
b = 19.4 m
at current speed 0.4 m/s
a = 279 m
b = 11.0 m.

Examination of the above data shows that in case of "instantaneous" (several days) release vast water area is subject to contamination.

At the time of subsequent release of activity from the NSSS of the sunken ship which is corrosive in its nature contamination of the water area is local in character and dictated by long-lived isotopes.

# 2. ANALYSIS OF INFORMATION SUPPORT TO ACCIDENT CONTROL

2.1. The common objectives of organisational and technical arrangements for accident control on board the nuclear ships are to prevent uncontrolled development of the accident to mitigate consequences thereof on board affected ship and outside it. These objectives are achieved through putting into effect a set of works that, from the standpoint of the time of their performance, concern the conditions of normal operational activity of persons and organisations involved in navigation in the Arctic Basin.

Among the mentioned arrangements, one of the principal one is drawing up a comprehensive emergency plan as a programme of actions that determines the ways of emergency confinement and minimisation of damage. The structure of such plan incorporates assessment of possible emergency situation, prediction of radiation doses, choice of protective measures, organisation of implementing protective measures.

Among the organisational and technical arrangements that are put into effect in the course of normal activity of the Russian nuclear ships are:

- drawing-up of the emergency plan;
- try-out of organisation and interaction of the emergency services;
- organisation of radiation monitoring on board the affected ship and in environment;
- organisation of hydrometeorological observations.

Drawing up and operational correction of the emergency plan, preliminary prediction and evaluation of the accident consequences, making of managerial decisions are impossible without reasonable informational support adequate to changes of the situation. Provision of informational and computing facilities on board the nuclear ships and in their operation management structures makes it possible set up an informational data base required for this purpose.

2.2. Stage-by-stage establishment of local computer networks is underway on board the nuclear ships, these being integrated, in accordance with the principal concept of the MMARMS functioning, into an Information System: ship-shore-ship where any subscriber can both send and make a request for information at the address of the other subscribers [2]. The data bank of the Russian Merchant Marine Automated Monitoring System is generated on the real-time basis, the information is documented and subsequently stored. Preliminary models of impact produced by an accident upon the environmental safety are generated in the board time system that is based on the zonal time. The board time is determined, corrected, stored by the navigating service personnel.

2.2.1. The hydrometeorological conditions during navigation of the ship vary continuously in time and space. Evaluation of the hydrometeorological conditions is based on the informational array of data contained in special manuals and current meteorological information supplied through the ship communication channels.

Software of the computer system to simulate radioactive particles carry-over process shall provide maintenance of the mentioned informational arrays to suit the navigational area of the ship with due regard for the requirements for furnishing information on existing radiation incident.

As a hydrometeorological source of information of statistic nature there is a need for input of data contained in sailing directions of the navigation areas. Among these data are:

- boundaries of the navigation areas;
- coast line;
- islands and straits;
- depths, sea bottom configuration and soil;
- special physical and geographical phenomena;
- prohibited areas;
- aids to navigation;
- ports and anchorage;
- repair and logistics support capabilities;
- pilot service;
- navigational information;
- communications;
- sailing particularities;
- meteorological characteristic.

2.2.2. The main climatic indicators are mean values of the meteorological elements, repeatability of gradations and variability of same. These indicators are determined from the observations of many years for each month, season and year with regard that the nuclear ships sail predominantly in the Arctic Ocean basin and in the north western part of the Pacific.

Organisation of acquisition and analytic treatment of the meteorological information on board the nuclear ships is governed by service documents universally adopted in the fleets and is not dealt with in this work.

2.2.3. To predict the accident consequences to a sunken ship data on hydrological characteristic of the likely site of accident shall be taken into consideration. Among such data are characteristics of:

- bottom configuration (continental shelf, continental slope and ocean bed);
- ground;
- water temperature and density;
- acoustic phenomena (density jumps);
- optic phenomena;
- ice and snow cover;
- sea currents;
- undulations;
- sea level fluctuations

Bottom configuration and presence of ground of an organic and inorganic nature affect the process of radioactive product transport depending on the climatic zone of the accident site in view of various intensity of the exchange phenomena on the molecular and ionic levels.

Salinity of water affects its density, freezing point and temperature at maximum density. The water density is a physical characteristic responsible for the motion of the world ocean waters. Vertical distribution of the density defines the condition of stirring aqueous medium. The characteristics of water density and acoustic phenomena depend on the geographical position and season of the climatic zone. The data are given in "Oceanological Tables" and "Sailing Directions for the Navigation Area".

Sea level fluctuations are caused by the atmospheric, hydrodynamic, geothermal and tidal phenomena. Among the non- periodic fluctuations are seismic (tsunami), off-and-on water and seiche one. Among the periodic fluctuations are tidal sea-level fluctuations. The height and temporal positions of levels depending on the location of port are given every year in the "Tide Tables".

Sea undulations are subdivided in respect to their nature of origin into:

- wind-generated;
- tidal;
- baric.

In addition to surface wave phenomena internal waves are generated in the interface of layers with different densities. The height of such waves amounts up to 20 - 30 m that results in change in the depth of oozy ground position. The characteristics of the wind- generated undulations depending on the geographical and climatic zone are given in "Nautical Table".

Currents are subdivided according to the following main features

- forces causing them;
- steadiness;
- depth.

The climatic and seasonal characteristics of the undulation elements are set out to a sufficient extent in the "Navigation Area".

2.3. Specifications for the hardware are defined by the major tasks and requirements imposed upon the System.

The tasks performed by the MMARMS are:

- continuous and on-line multiform monitoring of the state and time history of radiation situation;
- expeditious and reliable identification of the evidence of an accident, destruction of a radiationhazardous object;
- assessment of the category, character, scale and consequences of impairment of the radiation;
- situation on board the affected ship and in the neighbourhood thereof.

The main requirements with respect to purpose are:

- identification of the evidence of exceeding the background and specified EDR thresholds of ionising radiation in ships and fleet objects at the confidence coefficient not lower than 0.95 with cyclic information delivery:

at EDR > 200 mR/hr from 1 up to several minutes,
at EDR > 1 mR/hr from 10 min up to 1 hr,
at EDR > 30 mR/hr up to 1 day;

- assessment of activity, isotopic composition and dispersion of an aerosol component of an aerosol component, based on a probabilistic model of accident development;
- possibility of measuring EDR for gamma ray in the range from 10 to $10^9$ mR/hr within the range of spectrum energy from 0.05 up to 3 Mev;
- specification of activity and isotopic composition of the release according to the measurement data reference isotopes of the mixture in the area within more then 30 min after accident;
- zonal assessment of contamination level with a degree of certainty not lower than 0.98, their classification;
- specification of contamination level of a territory (water area), air space, flora and fauna by alfa-, beta-, gamma-ray isotopes based on periodic inspections;
- continuous monitoring with a specified periodicity of the time history of radiation situation of the regions and objects under control;
- delivery of information to the executive bodies to make managerial decisions as to confine and eliminate accident consequences with specified cycle;
- assessment of quantitative and list of factors of radiation impact on the population, flora and fauna subject to priority control;
- management of the MMARMS element functioning, monitoring the performance of same under the conditions of exposure of the system to radiation, climatic, geographical and other factors;
- technical feasibility of expanding the MMARMS information block on radiation situation with information arrays on chemical, biological and bacteriological situation.

The Information Network is responsible for performance of the following functions:

- documenting technical state of shipboard technical facilities and structures;
- accumulation of operating (statistic) data to generate probabilistic models of functioning elements of the shipboard and power-generating equipment;
- continuous integral evaluation of the technical state of the equipment in operation, prediction of pre-emergency situations;
- identification of the cases of improper actions by the operating personnel and faults of the instrumentation system from the generated statistic models;
- identification of the current wear-out factor of the on board equipment;
- fast acquirement of reference information on an arbitrary parameter from the generated data bases for each ship or a series of ships;
- presentation of objective information on technical condition of the ship and radiation situation on board to other subscribers in response to their requests as well as at certain intervals;
- continuous forecasting based on the probabilistic models of development of possible emergency situations and assessment of consequences thereof, periodical submission of this information to the subscribers and, at their request, to the organisations concerned;
- determination of the need for immediate transfer of the simulation results to the shore subscribers and establishment of automatic communication, if required;

- warning of the crew if in the process of simulation a dangerously high probability of an accident or emergency situation occurrence has been obtained;
- accumulation of the calculation results and initial data, keeping them during a certain period of time to generate "past history" of the accident;
- long-term storage of a certain scope of information based on the principle of the "black box";
- processing of input data to detect incorrect values;
- identification, on the basis of information on condition of the technical facilities, "weak members" which with maximum probability might be cause of the accident at a particular instant of time;
- simulation of an accident, reasoning from the concept of failure of weak member at a particular instant of time, while examination of the ways of development of an accident is carried out according to two forecasts: an optimistic one (considering criterion of single failure and proper actions of the crew) and pessimistic one (with increased failure of "weak members" and increased human errors);
- simulation of transmission of the radioactive products, attached to a particular geographical position after determination of a probable value of release into environment;
- determination of the most probable sequence of actions to be performed by the crew;
- determination of the list of shore-based and marine subscribers to which the information shall be conveyed in case of an accident;
- supply, at the request, results of the last cycle of simulation of the accident and after-effects thereof and in this case, requests from the subscriber affected by this accident upon completion thereof, shall be processed with the highest priority;
- storage of results of all the calculations and input data during a certain period of time.

The Information Network as regard communication channel shall satisfy the following main requirements:

- round-the-clock readiness of the communication channel, independent on the geographical position;
- high quality of the communication channel, probability of an error in transmission shall not exceed $10^{-6}$ 1/bit;
- complete automation of the process of convey and receipt of information.

2.4. Functioning of the Information Network is provided by software for subscriber call and automatic call establishment. A special feature of such a structure is use unified transmitting facility of the marine satellite communication when subscriber stations are set up onboard and on shore. In this case the network may operate in a single software environment. Information transmitted to the subscribers is subdivided into periodical, informative-forecasting and emergency.

In an emergency situation (including that when the monitoring parameters fall outside the set limits) the local information network of the ship obtains this information from the Centralised Monitoring System "Polus". Computer-dispatcher with the use the "Accident request" signal initiate communication with other subscriber of the monitoring system on the side of the ship and reports parameters of the emergency situation as well as forecast of its development made on the basis of statistical simulation. The information system is protected against the unpremeditated or premeditated distortion of the data, and also intervention into the process of calculation is prevented which makes it possible to "act-out" various emergency situations at request.

The last two provisions result in the fact that the shipboard portion of the system shall possess a true multiproblem nature. It shall include a 32-digit workstation based on two or three (and perhaps more) microprocessors Intel 80386 or Intel 80486. Speed of response of the system provides performance of the complete cycle calculation within 15 min for fast evaluation of the accident occurred.

The shore-based portion of the system shall provide;

- round-the clock readiness for immediate receipt of data from ships;
- possibility to make request from the shipboard portion about the results of simulation at the given instant of the time.

The shore-based subscribers may be considered as distant terminals of the information system and stringent requirements concerning computer power are not placed thereupon.

2.5. The informational support of simulation of scattering and distribution of the radioactive substances in the environment is based on use of various scattering models accessible from the standpoint of existing computing systems. Among these are:

- Gaussian models, the simplest, requiring information on wind speed and direction in the geographical point of the accident, atmospheric stability, height and release capacity. Use of these models gives fast evaluation of concentration in air in the near zone (5 to 10 km);
- Lagrangeian models, more complicated, require information on wind speed and direction over a considerable space; use of the said models gives realistic evaluation of the plume path of release and concentration in the nearest zone;
- three-dimensional models of movement and diffusion of the mixtures, require plenty of measurement of the wind speed and directions in vertical and horizontal extents with due regard for the affect produced by underlying surface and changes in the atmospheric stability over a vast area. The evaluations hold true up to 100-150 km from the geographical point of accident.

Mathematical technique for forecasting radiation impact with the use of the said models is widely known, for example, [4,5 etc.] and is omitted in this project.

2.6. Contents of the database of the Information System of INSROP contains subsystems covering: natural condition, information on natural environment, cartography of nautical regions, scenarios of accident consequences. In developing the system and integrating individual subsystems of the project consideration is being given to such circumstances as "Handbook of the Programme Project of Assessment and Monitoring in the Arctic, Arctic Initial Data Base GRID-Arendal" and "Handbook of Environmental Data of the US Arctic Geological Service". This database of an analytic system provides efficient access to the data sets for various purposes. Multifunctionality of the INSROP information system facilitates access to tabulated and cartographic data, integration of same and because of their analytic flexibility, solving of problem related

to emergency and postemergency management of navigation along the NSR.
Such multifunctionality of the Information System is based on appropriate protocols of entry in the international computer networks for all the subscribers. Among these are "Geographical Information System" - GIS in combination with the "Data Base Management System" - DBMS as well as the national informational and analytical Centres of Norway, Japan and other participants in the INSROP programme.

2.7. For informational support of the environmental safety of the navigation management in the Arctic with participation of the Russian nuclear ships The Informational Radiation Situation Monitoring System shall be integrated into the INSROP Information System on the basis of a common software, common communication protocols, common operation of various software and hardware, routing facilities. Such an Information Network shall be fairly reliable, provide protection against accidental loss of information, incorporate advanced data control facilities, contain facility for joint use of resources.

Such a system makes it possible, based on results of an analysis of the feasible versions of accident of the power plant on board a nuclear ship, maid within the scope of this project, to study a scenario of the consequences on navigation along the NSR and assess environmental safety in the adjoining region.

In view of the forgoing, there is a need becomes for further studying within the INSROP scope (or other programme of work in the interests of ensuring environmental safety of international shipping in the Arctic) the following aspects:

- organisation of interaction of the INSROP and MMARMS information system in the interests of localisation of a radiation accident and elimination the consequences thereof, with instructive indications for the order of joint access to the needed data bases;
- the order of furnishing information on radiation situation on board a nuclear ship at the request of the subscribers of the system under normal operating conditions of the NSSS with a list of a scope of data accessible to the subscriber;
- order and priority sequence of presenting information on radiation in case of an accident and results of probabilistic simulation of the accident development, radiation impact thereof on the environment including that at the request of the network subscribers;
- order of exchanging information with international information systems on the radiation incident, based on the proposed coded messages about the radiation situation.

Proposals for the coded messages about the radiation situation given in Appendix 1 may modify and improve depending on acceptance of the best version of the data base within the acting INSROP programme subsystems.

## 3. PLANNING OF ORGANISATIONAL AND TECHNICAL MEASURES FOR ACCIDENT MANAGEMENT AND MITIGATION OF ITS RADIATION EFFECT

3.1. Elimination of the accident consequence involving radioactive emissions beyond the limits of the NSSS protection barriers and mitigation of the accident effect may be successful, subject to implementation of a package of preliminary measures related in time to the period of normal (not emergency) operating conditions of the nuclear ships. Among the measures taken during the pre-accidental period the major part is played by the emergency plan and refinement of a organisation of interaction between various structures defined by this plan at various phases of the accident development.

The depth of elaboration of the plan and the score of its coverage of various conditions of use of the nuclear ships in navigation through the NSR in compliance with an International Arctic Shipping Programme are basic criteria of its practical usefulness. An universal plan for all cases of activity in navigation due to variety of factors (geographical, hydrological, weather, social) affecting activity under extreme conditions may not be worked out regardless of the concrete circumstances formed at that instant. Nevertheless such plans have a typical structure defining the programme of actions to reach success for all the package of measures mitigating impact of the accident on the ecological systems.

The emergency plan shall be an integral part of the regional measures to mitigate radiation effect produced by a likely accident of a nuclear ship. The agreed and approved emergency plans shall be accepted for execution in the process of normal navigational conditions within the INSROP score on appropriate levels of the administrative bodies of the programme and all the ships of the convoy escorted by the nuclear icebreaker, regardless of their nationality.

The experience of the world shipping shows that with the availability of an organisation to save human life at sea in compliance with good marine practice it a possible to reduce damage resulted from sea disasters to a reasonable minimum. In cases where the crew neglect or are not trained to initiate actions under extreme conditions the consequences of an ordinary navigational accidents grow into disastrous ones both for the personnel and the environment.

3.2. Typical scheme of the organisational and technical measures for elimination of the consequences and mitigation of the effect of an radiation of the accident is given in Table 3.1.

The trendy of the crew safety measures to prevent possible consequences of the radiation hazardous emergency situations, confinement thereof within the boundaries of protective barriers of a nuclear ship is given in Enclosure 2 "List of the Hazardous Situations"

**Table 3.1. Scheme of the Organisational and Technical Measures For Elimination of the Consequences and Mitigation of the Effect of the Radiation Accident.**

| Objectives, methods, means | Period of normal operation of the nuclear ship | Early and intermediate phases of the accident | Late phase of the accident |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| Objectives | 1. Rendering the ship and area of navigation insensible to the accident consequences.<br>2. Rendering the ship ready for patting the accidental and postaccidental measures mitigating the accident consequences into effect.<br>3. Forecast of possible accident consequences. | 1. Timely evaluation and forecast of development of the accident consequences.<br>2. Foundation of the need and choice of appropriate measures of radiation protection.<br>3. Taking the best decision on introduction of the social protective measures.<br>4. Implementation of the social protection measures. | 1. Precise evaluation of the accident consequences.<br>2. Foundation of need and choice of additional measures of radiation protection including environment.<br>3. Taking the best decision on introduction of the additional radiation protection measures.<br>4. Implementation of the radiation protection measures.<br>5. Recovering of the normal vital functions. |
| Methods to achieve objectives | 1. Development of the emergency plan.<br>2. Development and implementation of a package of technological measures o lower likelihood of the accident involving radioactive emission beyond the protective barrier of the nuclear ship.<br>3. Organisation of the structures of the Sipping Administration in accordance with INSROP, responsible for implementation of | 1. Organisation of activity of the appropriate organisational structures involved in the measures to mitigate consequences and eliminate the accident consequences to provide:<br>• evaluation of the radiation situation;<br>• taking decision on introduction of the best radiation protection measures.<br>2. Exploration and patting into effect of additional resources to implement protective measures.<br>3. Organisation of vital functions under post-accidental conditions.<br>4. Reorganisation of shipping and fishing within the accident impact region. | |

| Objectives, methods, means | Period of normal operation of the nuclear ship | Early and intermediate phases of the accident | Late phase of the accident |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
|  | pre-accident measures, particularly on board the ships.<br>4. Organisation of training and important of practical skill to the personnel of services responsible for initiation of emergency actions.<br>5. Creation of necessary logistics support to the measures for mitigation of the accident consequences. |  |  |
| Means to achieve objectives. | 1. Personnel of the nuclear ship, crews of the ships in convoy, Shipping Administration under INSROP Programme.<br>2. Technical facilities of the ships in convoy. | 1. Personnel of the nuclear ship, crews of the ships in convoy.<br>2. Personnel of organisations involved in elimination of the accident consequences.<br>3. Technical facilities of organisational structures for shipping through the NSR.<br>4. Additional material and technical resources. | 1. Personnel of organisations involved in implementation of measures to eliminate the accident consequences.<br>2. Technical facilities and material and technical resources of the accident impact region.<br>3. Material and technical resources of the Russia. |

The valid emergency plans are to be promptly revised in case of changes: organisational structures of shipping through the NSR; potentialities of the structures to organise protective measures to the transportation routes in the shipping basin, in the information systems, appointments to the posts.

When working out emergency plans for concrete ships in convoy in navigation through the NSR the following organisational and technical aspects shall be represented:

- determination on own ship's service (emergency response teams) responsible for initiation of the radiation protection measures;
- entering in the information subsystem to receive a warning signal and primary information on the nature of radiation hazard for the ships in convoy;
- establishment of predetermined protective measures (change of course, waiting at the lay time places), which, based on accident fact are used, should the need arise, right to the time of evacuation (abandonment of the ship) of the crew;
- working out the necessary instructions for the crew members patting in motion the top priority emergency measures;
- preparation of the technical facilities for radiation monitoring and protection of the crew against the possible radiation accident impact;
- arrangement of the control stations under extreme conditions; proper professional training of the members of the emergency-response teams;
- efficient methods of reviewing the emergency measure plans, communication systems and technical facilities used of that.

The organisational and technical difficulties in initiation of a package of actions in complain with the elaborated plan for the emergency use are overcame in the process of full-scale shipboard exercises and training within the convoy of ships.

3.3. Damage control of a nuclear ship is organised in compliance with the "Ship Damage Control Manual" and appendices thereto concerned with the nuclear ships which are basic documents defining order of carrying out preventive measures which are an integral part of the normal operation [6, 7].

Measures put into effect during normal operation include:

- observance of limits and conditions of the NSSS operation established by the service documentation;
- performance with an established periodicity of revisions of the NSSS control, protection and monitoring systems verification of the instruments with the use of the model units subjected to the State cheek, serves of safety equipment, periodical reviews thereof;
- maintenance, repair and replacement of the assemblies and components of the equipment;
- entries in the appropriate ship's logs of all the event and information related to the NSSS operation, maintenance and equipment checks;
- monitoring the radiation situation on board the ship, check the containment for tightness and air purification system for efficiency;
- check of operational reliability, and reliability in turning on the NSSS stand-by machinery and emergency power sources, heat removal system from the core and protective zone normal and emergency cooling system;
- check of Speed of controls insertion into the core;

- constant readiness of the communication system between the navigational bridge, machinery spaces, NSSS spaces, central and emergency control stations;
- maintenance of the proper professional training and qualification of the operating personnel and ensuring its psychological training in actions under extreme conditions.
-

3.4. The operating organisation provides:

- Manning of the ship with personnel in sufficient number who possesses proper qualification and trained in accordance with responsibility and duties established for crew of the nuclear ship;
- organisation of watchkeeping and supervision over the NSSS;
- keeping records of the NSSS operation, radiation situation, radiation doses of the personnel and all events associated with on malfunctions occurred and emergency situations in compliance with "Regulations for Classification , Investigation and Information Procedures for Malfunctions on the Nuclear Fleet Units [3];
- conduct of the scheduled NSSS and ship, damage- control drills with exercising in confinement of accidents, identification of radiation hazardous zones;
- availability on board of required valid service documentation including plans of measures to be taken if there is a threat of radiation hazard and "Radiation hazard" bill;
- drawing up and approval of long-term subject plans of crew training, exercise plans with use of imitation means;
- notification of the State Supervision Bodies and Management Bodies;

3.5. The port emergency plan is developed by the Port Authorities. The plan establishes management responsibility for management of all kinds of activity during nuclear or radiation-hazardous accident and defines organisation of the emergency team, its duties in case of an accident when the nuclear ship is in port and is developed with due regard for the fact that the actions on board the nuclear ship will be under control of the Master and correspond to the ship's emergency plans.

Staying addition to the ship's emergency plan envisages the following safety measures when the ship stays at the berth:

- determination of the order of using communication facilities contemplated by the port authorities;
- determination of the order of using shore-based fire-fighting facilities, special connections to supply the ship including shore electric power supply;
- determination fire fighting measures which are taken jointly with the port authorities and the procedure for immediate notification of the port fire brigades on the fire on board the ship and radiation obligation for the personnel involved on fire fighting;
- organisation of a guard to protect the ship and adjoining area against extreme actions which may cause damage to the safety of the ship;
- constant stay on board the ship: of the master or his responsible substitute out of the senior officers; of sufficient number of the crew members to enable implementation of all the emergency measures in case of an accident and propulsion of the ship if need be.

3.6. "Radiation Hazard" bills an integral part of the complex bill and defines responsibility and special duties of all the members of crew and establishes:

- underway watch complement on the main control station in the wheel house and chart room, central and emergency control rooms, in engine room, NSSS spaces;
- composition of the damage control party of the NSSS compartment, radioprospecting group and sanitary party;
- principle duties and actions of all the crew members participation in implementation of the emergency measures;
- main mustering positions on alarm of the damage-control parties and groups as well as the crew members not included into the damage-control parties and passengers.

The typical list of the crew actions on alarm "Radiation Hazard" is given in the "Damage Control Manual" and omitted in this report [6, 7].

During the stay of a nuclear ship in port a daily "Radiation Hazard" bill is drown up as a mandatory supplement to the staying complex bill.

When an emergency situation arises, which threatens safety of the ship or may result in carry-over of the radioactive products the Master must inform without any delay the operating organisation, other ships which are in the vicinity and the authorities of any coastal state which may be affected by the accident and send a notification of accident in compliance with the requirements of "Regulations for Classification, Investigation and Information Procedures for Malfunctions on the Nuclear Fleet Units" and "Notification System During Radiation Hazard on "Atomflot", ships with NPP and Nuclear Support Ships of the Sea Transport Department, Federal Law "On Use of Atomic Energy" [8].

In case where the radioactive substances are carried over in excess of the set standards, an appropriate signal according to the International Signal Code is hoisted on the ship:

- "AJ" - "I have a serious nuclear accident on board, you should approach with care".
- "AK" - I have a nuclear accident on board".

3.7. Responsibility and obligations of the Operating Organisation for ensuring safety of the nuclear plant, protection of the personnel, population and environment, notification and exchange of information in case of radiation hazardous accident on board a nuclear ship are established by Clauses 35, 36, 66, 68, of the Federal Law "On use of Atomic Energy".

## CONCLUSION

1. An analysis of the operating experience of nuclear ships shows that the reliability of systems ensuring nuclear and radiation safety, monitoring of radiation situation are kept at a sufficient level to confine development of the design-based accidents of the NSSS and provide environmental safety of the Arctic Shipping.

Due to high level of design and construction of the "Rossia" and "Taimyr" type icebreakers, proper professional level of the personnel operating the NSSS, fulfilment of requirements laid down by the programme of quality assurance of technical and technological maintenance and repair of the nuclear power plants, the probability of an non-design-based accident on these icebreakers is low (in the region of $10^{-5}$ to $10^{-6}$ 1/year) but cannot be reduced to zero and is completely precluded in the practice of the fleet.

2. Confinement of development of a non-design-based accident, mitigation its radiation impact on the ecological systems of the Arctic Basin down to an acceptably low level is achieved in the process of implementation of a package of the organisational and technical measures by the Operating Organisation in conformity with the normative, service and instructional documentation.

3. Preliminary development of a package of the organisational and technical measures, depth of elaboration of the emergency plan as a basis for actions to be initiated under extreme conditions make it possible to restrict radiation impact of a non-design-based accident on the personnel, population and environment down to an acceptably low level. Availability of an objective and opportune information on the accident characteristics, consideration of the climatic and hydrometeorological conditions in this case make it possible to assess the extent of risk for the international shipping in the Arctic.

4. The existing Marine Radiation Monitoring System provides informational data base required to manage accidents on board the nuclear ships and take managerial decisions concerning confinement of same and elimination of the radiation after-effects for the Arctic environment. However for the purpose of international shipping in compliance with the INSROP programme use of this informational support is a difficult problem due to linguistic differences in the software, routing of information flows and lack of the used programme adaptation protocols. With the aim of informational support in environmental safety in management of international navigation in the Arctic assisted by the Russian icebreakers work shall be performed to eliminate the above differences which hinder integration of the information systems with due regard for the Federal Law "On use of Atomic Energy" as regards requirements of international exchange of information on accidents on the nuclear plants.

List of the top priority works on integration of the information systems is given in Appendix 3.

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## Appendix 1

## REGULATIONS FOR CODED MESSAGES TO TRANSMIT INFORMATION ON RADIATION SITUATION

Exchange code: JA5 (ASCII). For all the transmission speeds where the total number of bits in the sequential character is equal to ten. Traditionally, the linear code is used (7 bit plus a bit to check for clearness) of the International alphabet No.5 (JA5) MKKTT (recommendations X4) equivalent to the American standard code for information interchange ASCII.

**Form for exchange radiological data proposed for use.**

| **Content of message** | **Code group** |
|---|---|
| Letter indicator of the code for radiological data (MiMiMjMj = RACO). Has to obligatory included in each codogram. | MiMiMjMj |
| Regular exchange: | 444 |
| Date and time of observations: | |
| - month (M) | YYM |
| - day (YY) | |
| - hours (GG) | GGgg |
| - minutes (gg) | |
| Position of the station which has made and transmitted observations: | |
| - latitude (LaLaLa), latitude code - 99 | 99LaLaLa |
| - longitude (LoLoLoLo), longitude code - Qc | QcLoLoLoLo |
| Index number of the station which has made and transmitted observations: | JJIIIiii |
| - republic code - JJ | |
| - district code - III | |
| - station's number - iii | |
| Radiological data: | 8TAAA |
| 8 - distinguishing digit | |
| T - indicator of the measurement interval | |
| To be coded according to Table 1; | |
| AAA - radiation level. | |
| Urgent message | III |
| Date and time of a nuclear accident: | |
| - month (M) | YYM |
| - day (YY) | |

| **Content of message** | **Code group** |
|---|---|
| - hours (GG) | GGgg |
| - minutes (gg) | |
| Position of the place where a nuclear accident occurred: | |
| - latitude (LaLaLa), latitude code - 99 | 99LaLaLa |
| - longitude (LoLoLoLo), longitude code - Qc | QcLoLoLoLo |
| Index number of the station which has made and transmitted observations: | JJIIIiii |
| - republic code - JJ | |
| - district code - III | |
| - station's number - iii | |
| Accident mode: | Ehhh |
| - instantaneous release of radioactive substances (E=1); | |
| - prolonged escape of gaseous or volatile radioactive products (E=2); | |
| - height of release in tens of meters (hhh) | |
| Possibility of transboundary transfer: | 550(1) |
| - transfer index - 55; | |
| - none - 0; | |
| - exists - 1. | |
| Gamma-radiation dose rate: | 2(3)TAAA |
| 2 - in plume; | |
| 3 - on the ground; | |
| T - indicator of the measurement interval To be coded according to Table 1. | |
| AAA - radiation level. | |
| Total concentration of gamma-activity: | 4(5)BBB |
| 4 - in a plume, Bk/m; | |
| 5 - under a plume, Bk/m; | |
| BBB - value of concentration. | |
| Content of individual radionuclides in the environment (I, Cs, Te, Pu, La, Zr - quantity and composition of the radionuclides is finalised in the process of development): | |
| - concentration in air (Bk/m) | 22200 |
| I | 1IIII |
| Cs | 2CsCsCsCs |
| Te | 3TeTeTeTe |
| Pu | 4PuPuPuPu |
| La | 5LaLaLaLa |
| Zr | 6ZrZrZrZr |

| **Content of message** | **Code group** |
|---|---|
| - concentration in water (Bk/m) | 22211 |
| I | 1IIII |
| Cs | 2CsCsCsCs |
| Te | 3TeTeTeTe |
| Pu | 4PuPuPuPu |
| La | 5LaLaLaLa |
| Zr | 6ZrZrZrZr |
| - density of fallout on the ground (Bk/m) | 22222 |
| I | 1IIII |
| Cs | 2CsCsCsCs |
| Te | 3TeTeTeTe |
| Pu | 4PuPuPuPu |
| La | 5LaLaLaLa |
| Zr | 6ZrZrZrZr |
| Total release of the gamma-active products and individual radionuclides, Ci | 333<br>SSSSS |
| Message at request | 666 |

**Table 1.**

| **Code digital** | **Interval of the measured radiation levels in within:** |
|---|---|
| 0 | 1- 999 μR/hr |
| 1 | 1- 999 mR/hr |
| 2 | 1- 999 R/hr |

Notes:

1) M - month (Symbolic number). To be coded: January - 1, February - 2, March - 3, April - 4, May - 5, June - 6, July - 7, August - 8, September - 9, October - 0, November - 6, December - 7;

2) YY: day of month to be coded: 01, 02, 03,..29, 30, 31;

3) GG - Hours of observation according to Greenwich mean time: GMT. To be coded: 01, 02, 03,..21, 22, 23. Number 24 in GG place is not used. Midnight refers to the coming day and is coded as "00". (in 44 Place in this case the date of the coming day is shown).

4) When transmitting information in the regular exchange mode to the next level of information processing the index number of the station which has made observation, comes only to the station of the district information processing. The provincial information-processing centre transmits to the republican (regional) level only the maximum value of radiological observations with indication of the code of the district where the said value has been received.

In so doing, any superior information-processing centre may obtain comprehensive information on the radiological observations at each observation station in any region at a special request. The volume of information at this case corresponds to the volume of the urgent message.

The form of exchanging data of hydrometeorological observations, expected to be used, corresponds to the data transmission codes: KH - 01; KH - 04; KH - 15 used in the network of the State Committee for Hydrometeorology.

- KH - 01: code for on-line transmission of data of the limiting hydrometeorological observations from the network of the stations of the State Committee for Hydrometeorology arranged on land (included shore-based stations), National version of the international code FM 12 - IX SYNOP;
- KH - 04: code for transmission of data of the vertical air sounding. Corresponds fully to the international code standards FM35. TEMP and FM36. E TEMP SHIP;
- KH - 15: code for compiling telegrams with the results of the hydrometeorological observations on rivers, lakes and reservoirs.

## Appendix 2.

## LIST OF RADIATION HAZARDOUS EMERGENCY SITUATION. [7]

| Emergency situation | Accident symptoms | Possible consequences | Aims of safety measures |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| 1. Rupture of primary circuit-accident with the loss of coolant. | Pressure drop in the primary circuit: level drop in pressure compensator; drastic increase in readings oh the radiation monitoring instruments: radiation levels and content radioactive substance within the containment spaces; pressure and temperature rise within the containment. | Threat of overheating and fusion of the core; threat to the crew members and other persons on board to be exposed to radiation doses exceeding established limits of the dose equivalent; threat of release or actual release of the radioactive substance to environment. | To render the reactor subcritical and remove residual heat from the core;<br>to confine accident within the limits of the containment and prevent propagation of the radioactive substances throughout the ship and in environment;<br>to minimise exposure of the crew members to radiation;<br>to supply power to the ship for actuation of safety systems and emergency propulsion;<br>to rescue and render medical aid and deactivate the victims;<br>to warn and evacuate the crew from the ship (if necessary);<br>to provide restriction and control over access to the radiation-hazardous zones. |
| 2. Leaks of the primary coolant into the containment or | Increase in activity in the containment spaces or circuits (to | Increase in dose rates in the containment spaces, in the | To defect, confine and stop leak, render the reactor sub-critical if the |

| Emergency situation | Accident symptoms | Possible consequences | Aims of safety measures |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| other process circuits not resulting in drastic pressure drop in the circuit. | be recorded by the radiation monitoring systems). | immediate vicinity of the engine room equipment. | leak cannot be stopped;<br>to prevent propagation of the radioactive contaminants and exposure of the crew member to dose exceeding the established limits; |
| 3. Failure of the main equipment or NSSS controls. | Operation of the warning and alarm signals. | When the leak-lightness of the primary pressure boundary is retained and heat is removed from the core there is no immediate threat of radiation hazard. When the heat removal process from core is disturbed emergency pressure rise is possible in the primary circuit and as a consequence, loss of leak-tightness of the primary pressure boundary. | To bring the NSSS in the operating mode contemplated by the service documentation, corresponding to a particular failure of the main equipment;<br>to provide heat removal from the core and retain leak-tightness of the primary pressure barrier. |
| 4. Ship's accidents.<br>4.1. Collision involving destruction in way of the NSSS compartment and engine room with subsequent flooding of these compartments (the ship remains be afloat). | Actuation of the warning and alarm signals. | Failure of the main and standby electric power sources, safety equipment and systems installed in the compartments flooded. | To render the reactor (s) sub-critical;<br>to provide removal of residual heat and retain leak-tightness of the primary-pressure barriers. |
| 4.2. Collision (or explosion on board the ship) involving rupture of the main steam line within the | Failures in operation of the systems and machinery. | Complete loss of electrical power supply before the emergency electrical power sources are started up (due to lack of steam); | To confine accident in order to prevent destruction of the bulk heads due to internal pressure;<br>to remove residual heat with the |

| Emergency situation | Accident symptoms | Possible consequences | Aims of safety measures |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
| containment. | | pressure and temperature rise within the containment, pressure rise in the primary circuit with possible consequences of its depressurisation. Actuation of the reactor cram trip. | secondary circuit system being failed;<br>to ensure safety of the SPP in compliance with the Operating Manual and Technological Instruction. |
| 4.3. Collision involving foundering of the ship in shallow waters. | Failures in operation of the systems and machinery. | Actuation of alarm and scram.<br>Emergency cooldown;<br>periodical interruption of heat removal to the sea water (the fourth circuit). | Failure to replenish few storage tanks in the tanks of the emergency cooldown system;<br>to provide heat removal to the sea water through the fire main or ballast system;<br>to supply electric power to the safety systems. |
| 4.4. Stranding. | Failures in operation of the systems and machinery. | Actuation of alarm and scram.<br>Getting a heel exceeding the limits within which the emergency electric power sources are capable to supply electric power (threat of a prolonged loss of electric power supply). | Periodical interruption of sea water supply (at falling tide); when it is possible to supply sea water to the condensers with subsequent use of fire and/or ballast systems;<br>to provide electric power to the safety systems. |
| 5. Fires.<br>5.1. Fire within the radiation barriers during power operation of the NSSS. | Operation of fire alarm, visual defection of fire areas by means of telecamera. | Emergency pressure rise in the primary circuit, threat of depressurisation of the primary pressure boundary; threat of explosion of the high pressure battles (if any). Threat of release of the radioactive substances to | To confine and extinguish fire;<br>to prevent explosion of the high pressure battles;<br>to prevent propagation of the radioactive substances and exposure of the crew to doses exceeding established standards. |

| Emergency situation | Accident symptoms | Possible consequences | Aims of safety measures |
|---|---|---|---|
| 1 | 2 | 3 | 4 |
|  |  | environment. Threat of damage to the PCCP cables, units of reactor control system and reactor monitoring systems. |  |
| 5.2. Fire in the CCR or adjacent spaces. | Operation of fire alarm, visual defection of fire areas. | Incapability of control and monitoring of the SPP operation and safety equipment. | To put urgently the SPP out of operation, control over the emergency cooldown and condition of the plant from the emergency control station;<br>to provide electric power supply from the standby and emergency sources of electric power;<br>to extinguish fire in the CCR. |

## Appendix 3.

### LIST OF THE TOP PRIORITY WORKS ON INTEGRATION OF THE INFORMATION SYSTEMS
### (IN THE ORDER OF PRIORITY GIVEN TO PERFORMANCE OF SAME).

1. Development of Regulations for an Automated Radiation Monitoring System within the scope of the INSROP Information System.

2. Development of an Instruction for the order of accessing data bank on radiation monitoring within the INSROP Information System.

3. Development of an Instruction for the order of exchanging information on radiation situation within the INSROP Information System.

4. Development of the technical support to the information network, including:
   - determination of the network layout with consideration for arrangement of the shore-based and shipboard subscribers;
   - particularisation of the types of the computing facilities, adapters, physical channels, rendering the network noiseproof;
   - specification and itemisation of the information flows;
   - organisation of the data base control system; graphs and information exchange protocols.

APPENDIX A

Helsinki University of Technology
Ship Laboratory

Otaniemi 9.5.1997

REVIEW OF THE REPORTS

V. Pravdin: Environmental Safety of Nuclear Icebreakers (1994 project work)

V. Pravdin, N. Tkachev and V. Levin: Environmental Safety of Nuclear Icebreakers.

Submitted to INSROP Project II: Environmental Factors, Project II.6: Environmental Safety of Navigation, II.6.7: Environmental Safety of Nuclear Icebreakers. Review performed by Dr. K. Riska, Helsinki University of Technology.

The present reviewer is NOT an expert in nuclear reactors or accidents in them, thus the review is a general one and made from a point of view of a naval architect.

Scope

The work carried out is related to environmental hazards from nuclear reactors in icebreakers. This topic is under a lively discussion in many fora and thus the selection of the theme of the research is very important. The study comprises, however, only a part of what a complete risk analysis should contain. The analysis of accidents and the consequence of these to the protection structures has not been touched at all.

Comments

The reviewer can place some general comments on the work as follows:

* The reports refer to the experience collected from operating nuclear power plants but not data or even references to support this are not given.
* The chapter 3. of the first report state the risks of damage to the power plant and the response of vessels in collision. No support to these statements is, however, given.
* An analysis of possible accidents and which are 'design-based accidents' could be given.
* The chapter on accident control should start from avoiding accidents.

Conclusion

The purpose of the reports is not quite clear as they are quite normative in nature. A detailed analysis of risks and hazards which could cause nuclear accidents might be given. The parts of the reports which require an expert in nuclear power plants should be reviewed by such a person.

Kaj Riska, Dr. Tech.

Tietotie 1
02150 Espoo
Finland

☎ (358-0) 4511

Telex
125161 htkk fin

Telefax
(358-0) 451 3493

## Appendix B.

## COMMENTS ON INSROP'S REVIEWER
## II.6.7. Environmental Safety of Nuclear Icebreakers.

On behalf of the authors of the Report express our deep thanks to Dr. Kaj Riska who took the trouble to examine the results of analysis of environmental safety assurance in Arctic navigation with the use of the Russian nuclear icebreakers, presented in the two parts of the Report.

As was pointed out by the esteemed reviewer, the topic touched is of high priority for INSROP.

Referring to the observations made by Dr. Kaj Riska it is necessary to note the following:

- the work (Part I) deals with the emergency situations in the "Rossia" and "Taimyr" type icebreakers contemplated in the technical documentation, the list of which is defined by the requirements of the IMO Code of Safety for Nuclear Merchant Ships, given in paragraphs: 1.3, 2.6, 2.7, 2.8, 6.1, 7.4 as well as in the Information on Nuclear Ship Safety Murmansk Shipping Company, 97, section: Analysis of Accidents and Failures;

- emergency situations not included in the nuclear accident list, contemplated in the technical and service documentation, are given in Table 1.1 of the Report, Part II.

- Section 3 of the Report outlines the whole package of the managerial and protective organizational and technical measures aimed at controlling the accident, mitigating the radiation aftereffects on the personnel, population and environment in compliance with the requirements of the IMO Code, Chapter 6, paragraphs 7.3, 7.4, Safety Information as well as the Safety Management Manual, SMS - 001. Safety Management System, Murmansk Shipping Company , 97. Sections: 1, 3, 4, 8, 10, 12, 13, 14.

Referring to the comments:

- The matter is not quite clear. The accumulated experience is generalized, analyzed and used in the design studies, performance specifications, normative and other documentation relating to the entire life cycle of the ship : from design and construction stage up to deletion. The operating experience is also reflected in the adequate professional training of the personnel who operate the shipboard NPP.

- The work presents the design values of shock loads which can cause damage of the NPP elements.
  The collision protection of the reactor compartment is made in compliance with the requirements of the IMO Code , paragraphs 3.1.2 - 3.1.4, USSR Register Rules, paragraphs 4 - 8.

- Analysis of emergency situations contemplated in the technical and service documentation is given in Part I of the Report, while the analysis of accidents, called by the esteemed reviewer as "possible", is given in Part II of the Report.

- Day-to-day activities of the personnel carried out in compliance with the Duty Regulations and service and technical documentation, performance of maintenance and repair work on NPP are aimed at avoiding and preventing accidents.
  Description of this work and requirements imposed thereupon is beyond the scope of this Report.

Referring to the conclusion:

A "detailed analysis of risks" which could cause nuclear accidents can not be given within the framework of this work due to a wide range of random factors which affect the random process of accident development. The Report points out that there is a need to have within the INSROP framework organizational structures capable to make managerial decisions for mitigating radiation impact on ships in a convoy escorted by a nuclear icebreaker, in case of a nuclear accident.

Yours sincerely V. Pravdin, Supervisor

P.S. I feel certain that most of the points touched by the esteemed reviewer might be eliminated, during personnel contracts.

With kind regards and thanks V. Pravdin, Supervisor

Institut for Fysik
Danmarks Tekniske Universitet

APPENDIX C

Claes Lykke Ragner
INSROP Programsekretær
Fridtjof Nansens Institutt
Lysaker
Norge
Fax: 0047 6711 1910

2 juli 1997
PLØ

Kære Claus Lykke Ragner,

Nedenfor skal jeg fremkomme med en række kommentarer til de to rapporter, som Du har sendt mig til udtalelse, om miljøforhold ved nukleart drevne isbrydere i forbindelse med INSROP. Af hensyn til eventuelle andre, som måtte være interesserede i kommentarerne, har jeg affattet dem på engelsk.

## SOME COMMENTS ON TWO INSROP-DISSUSSION PAPERS
### (Environmental Safety of Nuclear Icebreakers)

The two reports deal with the risk and consequences of design and non-design basis accidents with nuclear icebreakers. It considers the two major types of accidents, reactivity accidents and loss-of-coolant accidents, in addition to collision and grounding.

It is, however, not possible for a number of reasons to make a definite assessment of the analyses performed.

Firstly, no description of the reactor system considered and in particular of its safety system is given. Such a description does undoubtedly exist (see page 2-I of the report of 20 April, 1995), but probably only in Russian. Since it is the starting point of any safety analysis, it is difficult to make any assessment of the results obtained without this information. It seems that the Russian icebreakers are provided with the safety systems required in the West such as emergency core cooling systems, residual heat removal systems, containment etc. but a description of these systems is needed. An important aspect of western reactor safety systems is the defence in depth, i.e. several systems exist so that if one does not work, the next will take over.

Secondly, no decription of the models or computer programmes used in the analysis is given. Again without this information it is not possible to make an assessment of the analysis.

Thirdly, the text is often very difficult to understand. To give one example, on page 2-II in the report of 25 March, 1996 the following statement is made: "In case of an accident involving initiation of a spontaneous fission chain reaction due to fusion of the core "hot particles" are likely to be generated

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Institut for Fysik

bygning 309
2800 Lyngby

telefon:
45 88 16 11

telefon direkte:
45 25 34 55

email:

fax:
45 93 16 69

Institut for Fysik

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within the fission products". I do not understand the meaning. Is it "In the case of a run-away chain reaction accident (also called an reactivity accident) melting of the fuel is likely to result due to the decay heat of the fission products"? Or what is it?

For these reasons it is not possible for me to make an assessment of the results presented in the two reports. I have, however, some comments to various statements in the reports.

In the report of 20 April 1995 it is stated on page 5 that the operating experience of the Russian nuclear icebreakers since 1960 shows that the probability of a nuclear heavy radiation accident is extremely low. It does not mention that in 1966 the icebreaker NS Lenin suffered a severe loss-of-coolant accident with damage of the fuel, so that the damaged reactor power plant had to be replaced by a new plant. The accident did not happen during operation, but during refueling, but it happened never the less.

In the report of 20 April, 1995, it on page 2-II stated that "Outflow of the radioactive substance outside the containment is feasible due to operation of the safety valve and through the compartment vessel untightness, which may be the highest possible in operation (at a rate of 10 vol% per hour)." If this statement means that the leak from the containment can be 10 vol% per hour, the containment is of quite low quality.

In the report of 25 March 1996 it on page 2-I and on page 5 mentioned that the probability of an accident not contemplated in the technical documentation is slight, in the region of $10^{-5}$ to $10^{-6}$ per reactor year. No basis for these figures is given. If one looks on the nuclear safety experience of the Soviet Navy the risk is significantly higher, about $10^{-3}$ per reactor year.

My conclusion is therefore that it is not possible based on the the two reports to make an assessment of the nuclear safety of the Russian icebreakers. It may be OK or it may not be OK.

Let me end by pointing out that nuclear safety is not only a matter of having a good plant design. Of equal importance is high quality manufacture, thorough training of the personnel and a high safety culture. The safety culture of the Soviet Navy was not impressive, but it may be different for the Russian icebreaker fleet.

Jeg håber, at ovenstående kan være til nogen nytte for Jeres projekt. Lad mig samtidig nævne, at en egentlig gennemgang af sikkerheden i et reaktoranlæg er et stort arbejde, som vil kræve mange mandmåneder.

Med venlig hilsen

Povl L. Ølgaard

## Appendix D.

## COMMENTS ON INSROP'S REVIEWER
## II.6.7. Environmental Safety of Nuclear Icebreakers.

A good deal of work has been done by the esteemed reviewer to examine the Reports related to the aspects of ensuring safe navigation in the Arctic, assisted by the Russian nuclear icebreakers within the INSROP program framework. As it is noted in the review the report considers various types of nuclear accidents as well as collisions with the nuclear icebreakers.

The reviewer gives a number of reasons for which he cannot "make a definite assessment" of the work.

It is necessary to make the following comments.

1. The report refers to safety systems of the "Rossia" and "Taimyr" type nuclear icebreakers. The said systems complies with the requirements of the "Code of Safety for Nuclear Merchant Ships. IMO Resolution A. 49 (XII) of 19.11.1981 and the "Rules for the Classification and Construction of Nuclear Ships. Register of the USSR". Description of the safety systems of nuclear ships as exhaustingly given in the "Ship Safety Information", takes up considerable space including necessary drawings, diagrams and graphs of controllable parameters. The mandatory availability of such information on board the nuclear ship suits the requirements of the Charter, IMO Code and USSR Register.

We see little reason for presenting description of the safety systems in such a Report which has not for an object to assess structural features of the said systems. The more so as these systems have been made in compliance with the requirements of both the national documents of the USSR Register`s Rules, p. 50 - 88, 110 - 118 and the international documents : IMO Code Chapter 4, 6 (English edition).

2. The cited assessments of radiation impact on the environment have been made using a conservative approach presented in the works of the NPP Designer, our investigations on safe operation of the nuclear icebreakers. Use therewith has been made of well-known typic models of radioactive substance transport in air and aquatic environment. Appendix 3 presents, a list of top priority works aimed at devising an INSROP information system the software of while shall be based on the calculation models and algorithms which are presently a confidential information in Russia.

3. The Report has been drawn up using terms and definitions accepted in the above-mentioned "Code of Safety for Nuclear Merchant Ships". IMO Resolution A. 491 (XII) (English edition).

A misprint has stolen in the example given, which was rectified in the Summary Report. The case in point here is the sublimation of structural materials of the fuel composition and reactor core in addition to the fission products of nuclear fuel.

Referring to the comments made :

a. In this comment it is noted that the accident the icebreaker NS "Lenin" met with, has taken place not under sailing conditions but during modernization work when the experimental three-reactor NPP was being replaced by a commercial two-reactor plant which has completed trouble-free its service life aboard the ship right up to inactivation of the lather.

b. As stated on the mentioned page of the Report, outflow of radioactive substance through the safety valve of the reactor compartment vessel has been contemplated in the ship design and is an emergency outflow through the ventilation system. Owing to filtration only radio active inert gases of krypton-xenon group are vented into the atmosphere. The stated outflow rate is given as a reference rate for subsequent assessment of the accident effect and not as a characteristic of the compartment vessel untightness, which is suited to the requirements of the IMO Code, USSR Register and is reflected in the Safety Information.

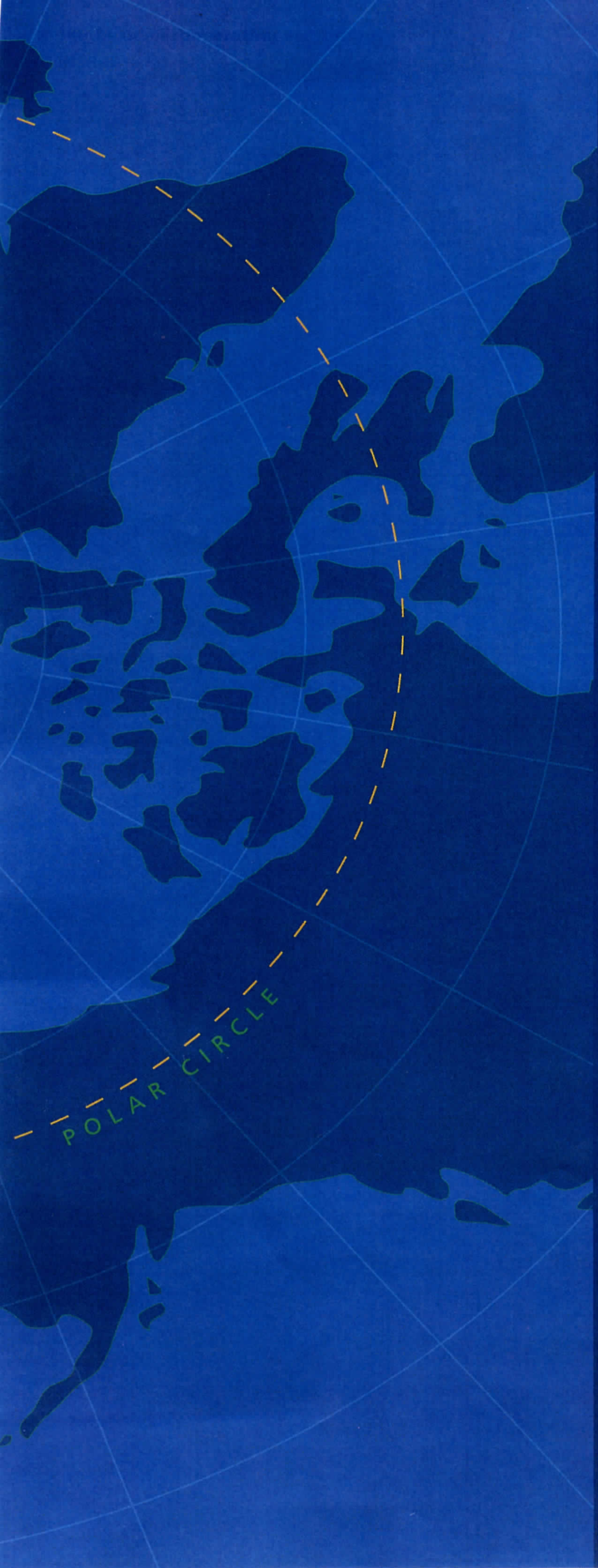
c. Throughout the whole operating period of the Russian nuclear icebreakers in the Arctic not only the non-design-based accidents but also the design-based ones involving impairment of radiation situation, have not been recorded on these ships. From this it may be inferred that the likelihood of a non-design-based accident which can occur on board the "Rossia" and "Taimyr" type nuclear icebreakers is rather low.

d. The aim of the work presented to assess the potential radiation hazard which has to be foreseen.The experience of the world shipping shows that the element of a navigational hazard exists at all times. If this hazard is taken into account ship`s accident does not generally entail disastrous consequences. The work presented gives ways, methods and means to control an unlikely but none the less possible radiation accident, which make it possible it reduce the radiation damage to the personnel, population and environment to a minimum.

Sincerely your V. Pravdin, Supervisor

P.S. I feel certain that most of the points touched by the esteemed reviewer might be eliminated during personnel contacts of the author with the experts who took the trouble to examine the work submitted for their appraisal.

With best regards and thanks V. Pravdin, Supervisor



## The three main cooperating institutions of INSROP

**Ship & Ocean Foundation (SOF), Tokyo, Japan.**

SOF was established in 1975 as a non-profit organization to advance modernization and rationalization of Japan's shipbuilding and related industries, and to give assistance to non-profit organizations associated with these industries. SOF is provided with operation funds by the Sasakawa Foundation, the world's largest foundation operated with revenue from motorboat racing. An integral part of SOF, the Tsukuba Institute, carries out experimental research into ocean environment protection and ocean development.

**Central Marine Research & Design Institute (CNIIMF), St. Petersburg, Russia.**

CNIIMF was founded in 1929. The institute's research focus is applied and technological with four main goals: the improvment of merchant fleet efficiency; shipping safety; technical development of the merchant fleet; and design support for future fleet development. CNIIMF was a Russian state institution up to 1993, when it was converted into a stockholding company.

**The Fridtjof Nansen Institute (FNI), Lysaker, Norway.**

FNI was founded in 1958 and is based at Polhøgda, the home of Fridtjof Nansen, famous Norwegian polar explorer, scientist, humanist and statesman. The institute spesializes in applied social science research, with special focus on international resource and environmental management. In addition to INSROP, the research is organized in six integrated programmes. Typical of FNI research is a multidisciplinary approach, entailing extensive cooperation with other research institutions both at home and abroad. The INSROP Secretariat is located at FNI.