РОССИЙСКАЯ АКАДЕМИЯ НАУК
Институт проблем безопасного развития атомной энергетики
RUSSIAN ACADEMY OF SCIENCES
Nuclear Safety Institute (IBRAE)

Russia's efforts to improve safety following the Chernobyl and the Fukushima accidents

Leonid Bolshov

Post Chernobyl efforts

SU/Russia changed attitude to SA:

- Science based approach
- Internationalization
- Studies of DiD phenomena and models
- Scenario analysis
- Harmonization of regulations (INSAG-3)
- Modernization of all NPPs
- Upgrade of the Russian emergency response system and Rosatom emergency system

Basic Safety Principles

LEGISLATIVE BLOCK

- Federal laws (principles of responsibilities)
- System of norms and regulations
- Availability of state licensing system (independent regulation)

SAFETY CULTURE

- Priority ranking
- Human factor

TECHNOLOGICAL BLOCK

(Technical provision of safety)

PRINCIPLE OF DEFENSE-IN-DEPTH

- Multiple safety barriers
- Diverse levels of safety barriers
  - accidents to be prevented
  - mitigation of accident consequences (emergency management)

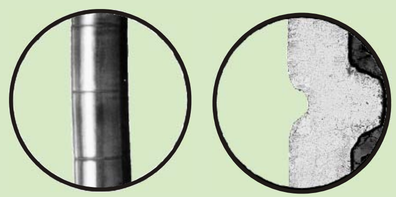
BASE of KNOWLEDGE about processes and phenomena

Reactivity accidents

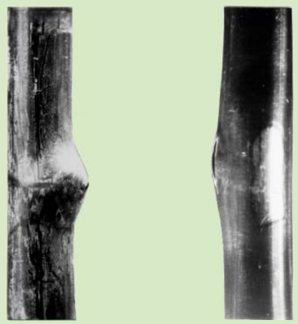
various types of fuel rod destructions

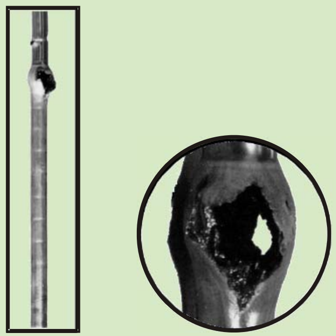
CLAD BREACH

Clad cogging over fuel pellet boundary



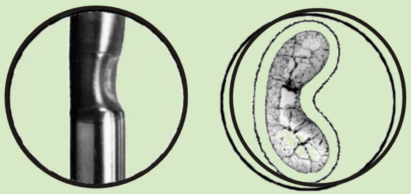
Fuel rod with high burn-up (left) and with fresh fuel (right)



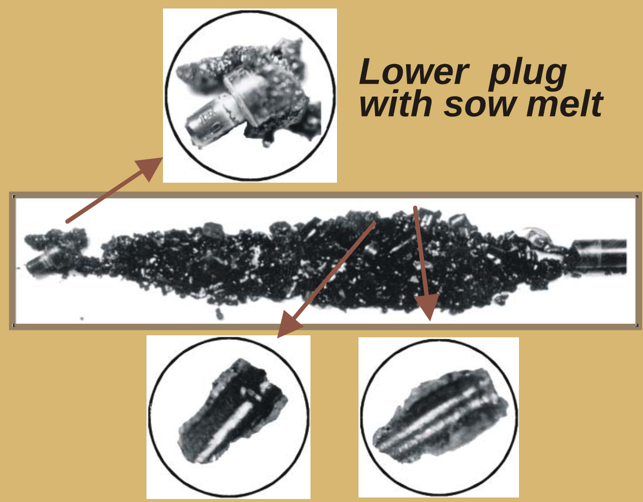


Specific swelling with clad breach

Cross-section of fuel rod with maximal deformation



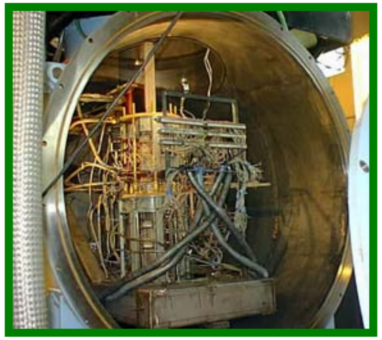
FUEL ROD FRAGMENTATION



Lower plug with sow melt

Fuel pellet fragments with melted-out central cavity

Loss of coolant accidents

RASPLAV	MASCA
 	  

In vessel melt retention

- Database on thermal physical properties of corium contains data for temperatures up to 3100 K
- Database of crucial parameters describing the molten pool behavior was created
- A tool for analysis was developed

Change of Russian Safety Concept (INSAG-3)

- **OLD SAFETY CONCEPT**

1. In-depth analysis: design basis accidents and postulated initiating events

2. Number of registered failures during evolution of design-basis accidents is limited to the principle of a single failure

- **NEW SAFETY CONCEPT**

1. Analysis of beyond-design-basis accidents with possible severe damage of reactor core up to its full melting

2. A principle of a single failure is withdrawn while analyzing the beyond-design-basis accidents

Development of safety requirements

- Toughening the requirement of various defense levels independence, minimization of possibility of accident development at next stages
- Radiation risk in all conditions and modes should be comparable with the risk from other industrial installations used for similar purposes
- There should not be a necessity in evacuation out of the plant site
- Requirements on placing the nuclear installations should not contain additional restrictions in comparison with other industrial facilities

Post Chernobyl efforts

Adoption of safety culture principles:

- Priority of safety in design, construction and operation in general and day-to-day management
- Education and training programs
- Full scope simulators at every plant

Post Chernobyl efforts

Cleaning and remediation

- Cleaning of contaminated areas after Chernobyl
- Medical screening
- 1990 Extraordinary protection measures
- 1994 Conversion of federal programs from saving lives to social rehabilitation

Efficiency of water protection measures at the Chernobyl NPP and their environmental effects

Countermeasure	Localized ^{137}Cs activity, TBq	Cost, 10^6 dollars	Indivi-duals	Specific cost, dollars/MBq	Environmental effects
Filtering dam system	0.074-0.11	46	3000	420-620	Forest flood in 4000 hc
Wells in riverbed	0.44-0.74	50	500	68-114	4.5 mln. m^3 sand capture, which sand could cover ooze sediments in Kiev reservoir
Pond-cooler isolation	< 0.037	> 100	> 1000	> 2700	Elevation of ground waters in the Chernobyl NPP site

Comparative efficiency of protective measures related to reduction of radiation exposure

Countermeasure	Range of individual averted doses, mSv	Range of reduced costs, dollars per 1 man Sv	Experience (place, time)
Emergency relocation	13,000-23,000	300-600	Urals, October 1957
	100-3,000	1,000-15,000	Chernobyl, April - May 1986
Relocation	40-200	6,000-100,000	Urals, November 1958
	50-100	130,000-500,000	Chernobyl, 1990-1991
Relocation of children and pregnant women	< 1-40	4,000-400,000	Chernobyl, May - September 1986
Sheltering	5-100	0.02-1	Pripyat, April 26 and 27, 1986

Costs of countermeasures after the Chernobyl NPP accident

Countermeasure	Range of reduced costs, dollars per 1 man Sv, man Gy	Experience (year, place, contingent)
Iodine prophylaxis	0.02-0.1	1986, Pripyt population
Sanitary treatment	25-500	1986, Chernobyl NPP area
One week refusal of milk consumption (children)	1-15	1986 Children of contaminated areas of the Ukraine
Restriction of consumption and control of local foodstuff	2,800-25,000 8,600-68,000 13,800-120,000	1986, Bryansk region 1987, Bryansk region 1989, Bryansk region

Chernobyl experience

Contamination density	Average dose, mSv	Area, km^2	Population, thous.
> 15 Ci/km^2 (555 kBq/m^2)	10	11000	85
> 40 Ci/km^2 (1480 kBq/m^2)	40	3620	7

In accord with the "Chernobyl Law" in 1991, the territories contaminated with Cs above 1 Ci/km^2 were assigned with the affected lands. The total area comprised 160 thous. km^2 with the population of about 3 million.

As the Chernobyl experience showed, the excessive and radiologically unjustified protective measures (primarily evacuation) could lead to a sharp amplification of negative psychological, social and economic consequences.

Legacy issues

During restructuring of economy after SU disintegration, a number of back-end and legacy issues are being solved:

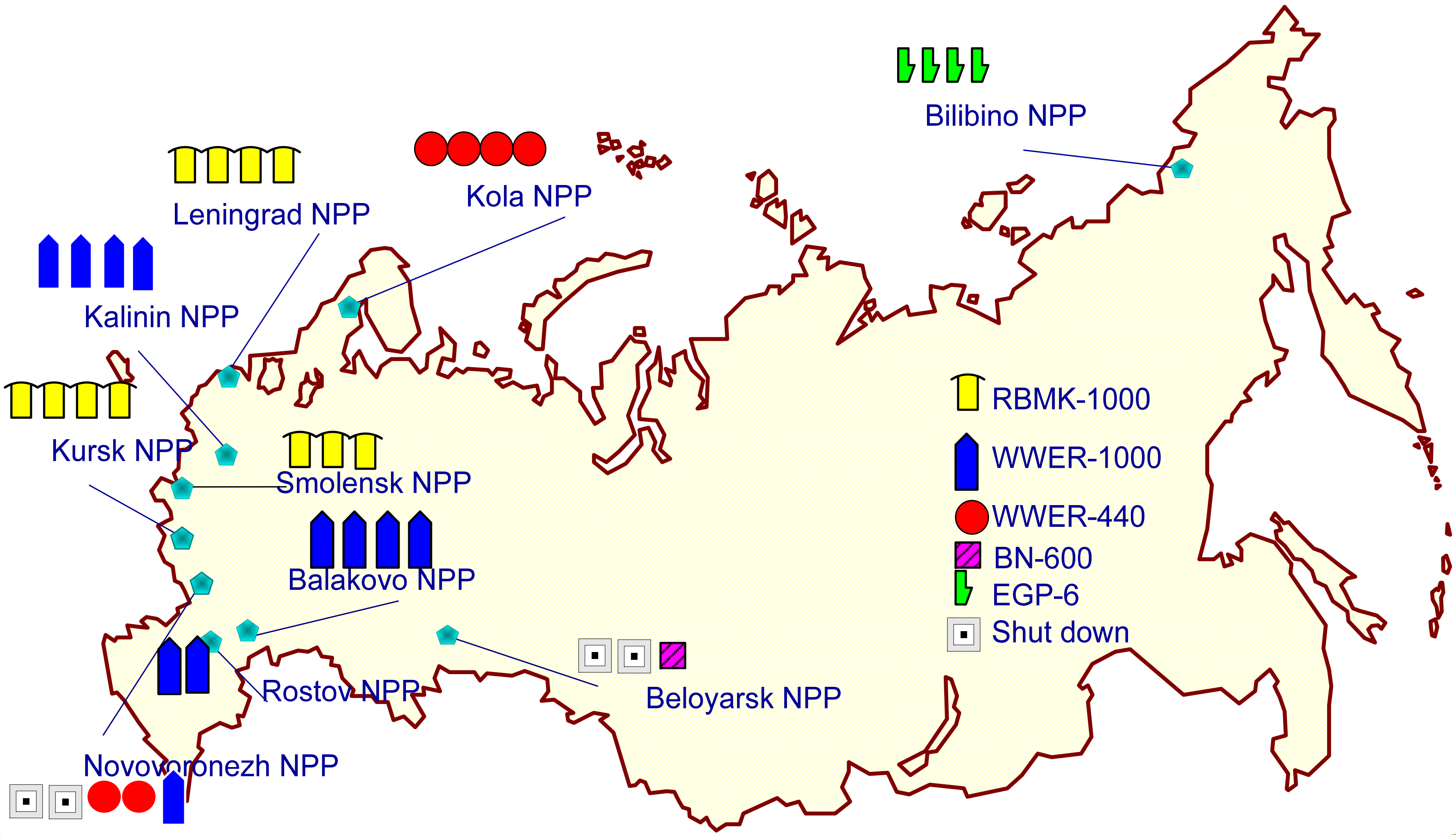
- Since 2008, a large-scale Federal Program addressing legacy and back-end issues is in progress
- Safety of waste and SNF storage improved
- Centralized dry storage of SNF built
- 2011 Federal Law on Radioactive Waste Management had set a limit for temporary storage and necessitated ultimate disposal of all wastes

Russian nuclear program

- Large scale domestic construction of VVER-1200 (Kaliningrad, Leningrad-2, Rostov, Novovoronezh-2, Nizhniy Novgorod, Kursk…)
- VVER-1200 foreign constructions (China, India, Turkey, Vietnam,…)
- Fast reactors with closed fuel cycle R&D program (Beloyarskaya BN-1200, BREST,…)
- SMRs (floating, SVBR, VBR, VVER-640…)

Operating Russian nuclear plants

10 NPPs, 33 units, $N_{inst.}$=25242 MW

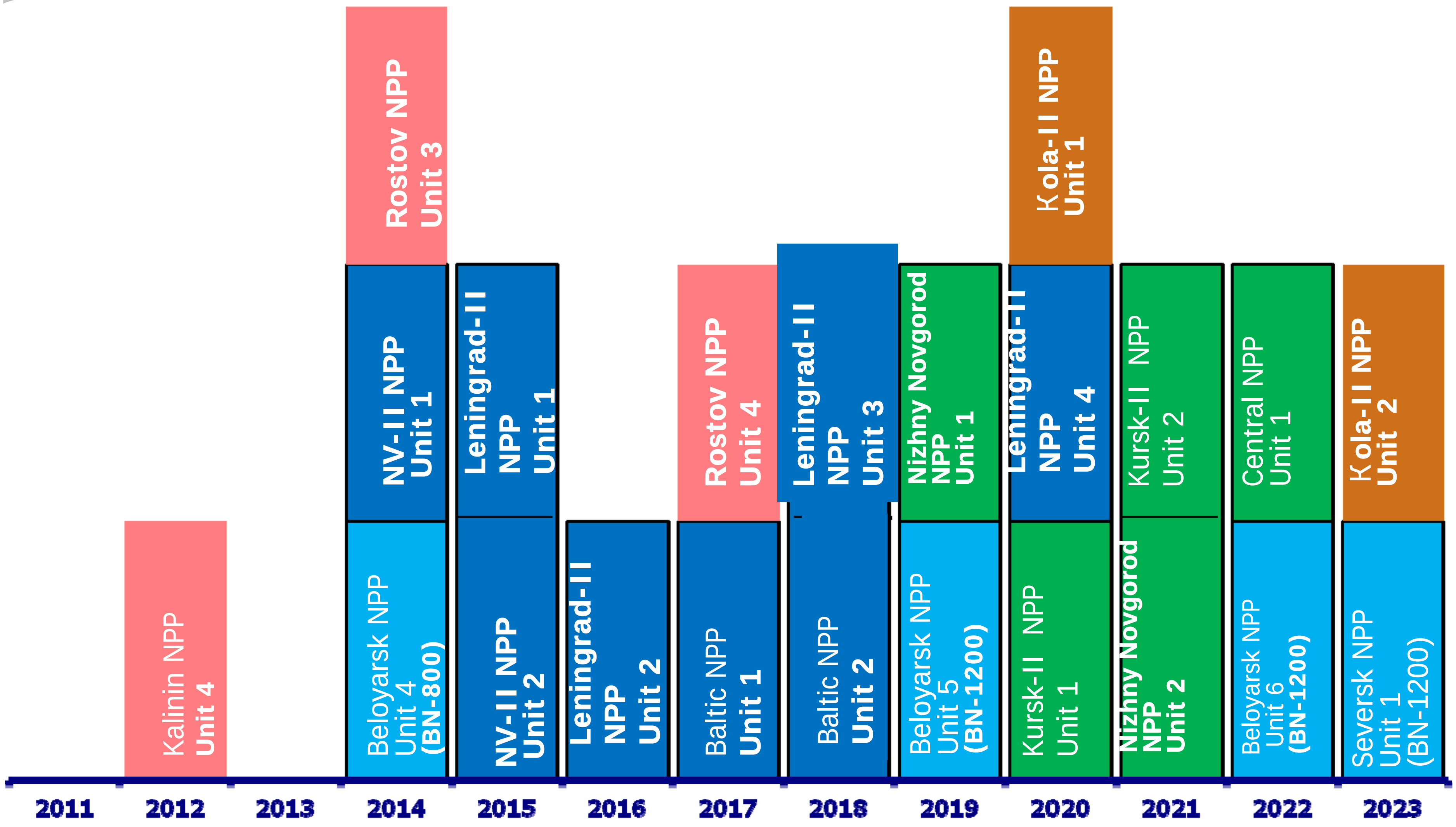


NPP Operator - JSC "Concern Rosenergoatom"

Rosenergoatom was established on 07.09.1992 as NPP Operator by the RF President's Decree

33		- number of existing power units
25242	MWt	- the installed capacity
177.3	bln kW-h	- generated in 2012
35	thous. pers.	- Rosenergoatom's employees

Russian nuclear power roadmap



The Number of Deaths and Early Effects of Radiation Accidents Based on published data (except for malicious acts and nuclear weapon tests)

Type of accident	1945-1965	1966-1986	1987-2007	Total	Opinion of the Committee regarding the Report completeness
Accidents at nuclear facilities	46 early effects	227 early effects *	2 early effects	275 early effects	Most of the deaths and many injuries were likely reported.
	16 deaths	40 deaths*	3 deaths	59 deaths	
Occupational accidents	8 early effects	109 early effects	49 early effects	166 early effects	A number of deaths and injuries were not likely reported.
	0 deaths	20 deaths	5 deaths	25 deaths	
Incidents with orphan IRS	5 early effects	60 early effects	204 early effects	269 early effects	A number of deaths and injuries were not likely reported.
	7 deaths	10 deaths	16 deaths	33 deaths	
Accidents during research projects	1 early effect	21 early effects	5 early effects	27 early effects	A number of deaths and injuries were not likely reported.
	0 deaths	0 deaths	0 deaths	0 deaths	
Accidents during medical use	no data	470 early effects	143 early effects	613 early effects	It is evident that many deaths and a significant number of injuries were not reported.
	no data	3 deaths	42 deaths	45 deaths	
TOTAL					
Early effects	60	887	403	1350	
Deaths	23	73	66	162	

Table 10 p.52 of Appendix R.671 to the UNSCEAR 2008 Report

Summary Data for Major (> 5 Victims) Accidents in the Energy Sector in 1969-2000

	OECD countries			Non-OECD countries		
Type	Accidents	Victims	Victim/GW	Accidents	Victims	Victim/GW
Coal	75	2259	0.157	1044	18 017	0.597
Coal (data for China, 1994-1999)				819	11 334	6.169
Coal (excluding China)				102	4831	0.597
Oil	165	3713	0.132	232	16 505	0.897
Natural gas	90	1043	0.085	45	1000	0.111
Oil & gas	59	1905	1.957	46	2016	14.896
Hydropower	1	14	0.003	10	29 924	10.285
Nuclear power	0	0	-	1	31*	0.048
Total	390	8934		1480	72 324	

* Instant deaths only

What was wrong?

- Main safety objective: the protection of the public from excessive exposure, is not accurate.
- Core melt accidents with low or no radiation effects used to have large scale consequences because of public illiteracy, contradictory health regulations, bad communication…

General outcome of the Fukushima Daiichi accident

1. It is now clear that many factors contributing to the Fukushima accident were identified prior to the accident:
   - *poor severe accident management planning structure;*
   - *lack of safety improvements;*
   - *inadequate evaluation of external hazards;*
   - *weak regulatory system;*
   - *lack of training of personnel on emergency preparedness.*

2. The necessary measures to address these shortcomings were not put in place.

Tests of defense-in-depth efficiency have been done:

1 - for each power unit in operation in Russia

2 - taking into account all credible extreme impacts on NPP that are specific for the placement region

3 - taking into account various combinations of the extreme impacts

Results of the in-depth assessment

1. Upgrading works aimed at safety improvement of NPPs have been implemented during last 10 – 15 years

2. Vulnerabilities and initial events have been revealed for each NPP

3. Implementation of supplementary measures aimed at enhancement of NPP robustness is needed

4. Not all BDBA initial events were considered in designs of the operating NPPs

- Total loss of heat removal from the reactor core
- Complete and durable (over 10 days) loss of NPP connections to external power sources
- Combination of 2 or more independent initiating events

Additional measures to improve safety of Russian NPPs

Near-term actions

- Purchasing and equipping the plants with portable engineering means to be used for elimination of severe BDBAs:
  - **Diesel generators,**
  - **Diesel-driven pumps,**
  - **Motor-driven pumps, etc.**

Medium- and long-term actions

- Analysis and development of specific supplementary design solutions to be implemented at each NPP

Introduction of mobile emergency equipment at NPPs

In 2012, the following equipment was delivered to 10 Russian NPPs:

31 units

Mobile diesel-generators 2.0 MW (6kV; 0.4 kV; 220 V DC)

36 units

Mobile diesel-generators 0.2 MW (0.4 kV)

35 units

Mobile high-pressure pumping units of various capacity and head pressure

80 units

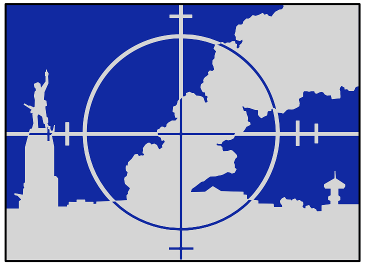
Engine-driven pumps of various capacity and head pressure

TOTAL: 182 units

Scale of the Problem

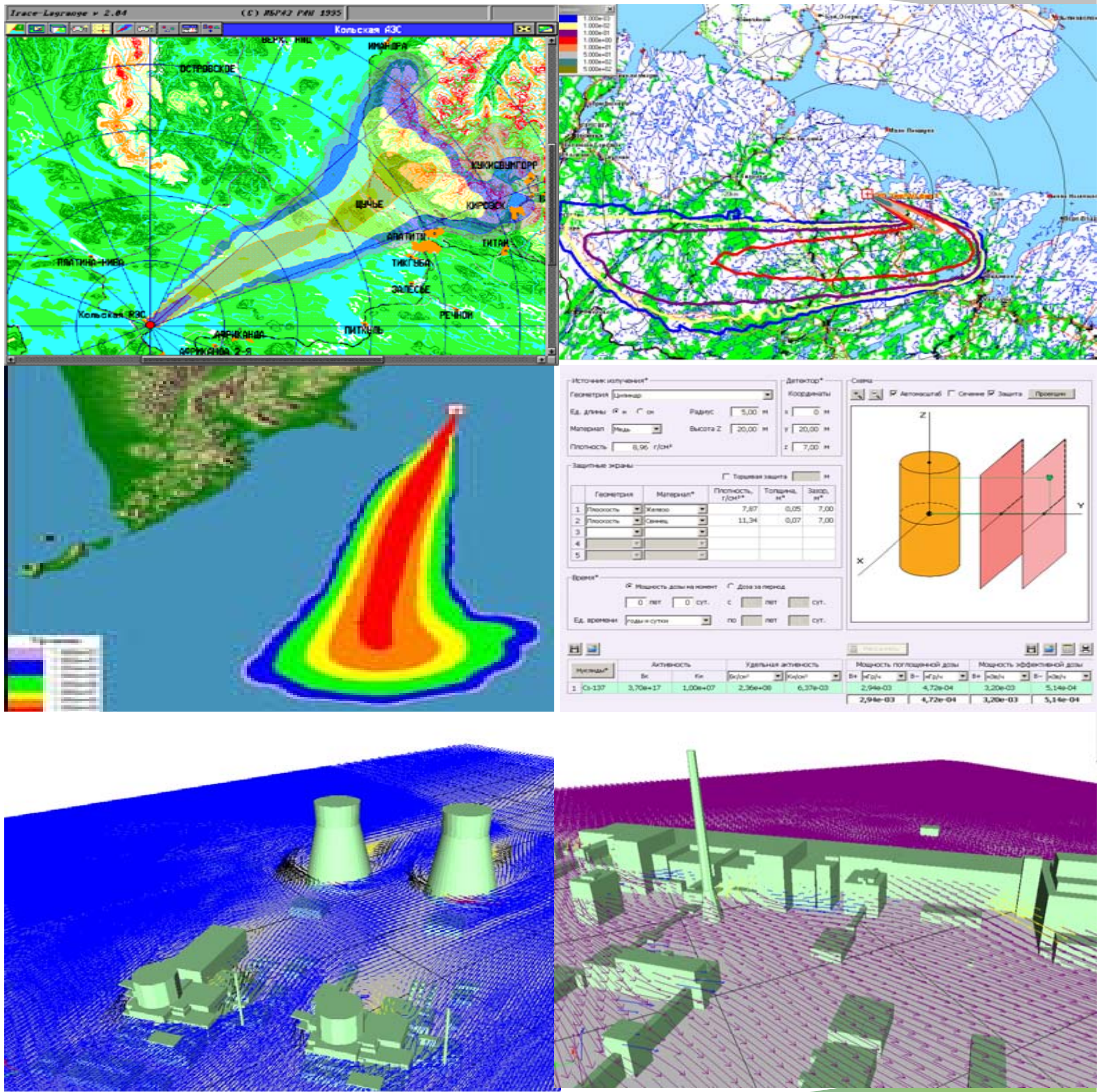
What do you know about the victims of military and peaceful atom?

Students

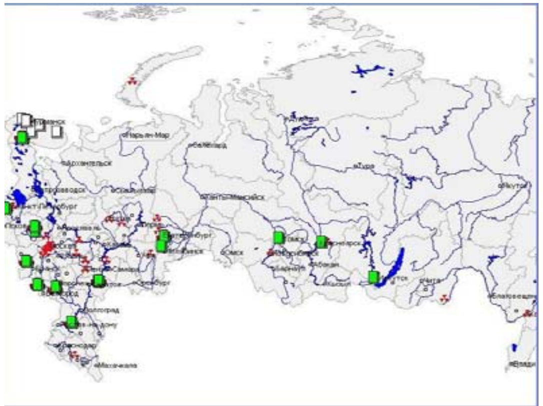
Event	Real number of victims	Students' evaluations
 Hiroshima	Immediate and quick death of 210 000 people	About 300 000 people
	Remote consequences among 86572 hibakushas – 421 people	750 000 people
 Chernobyl	Immediate and quick death of 31 people	40 000 people
	Remote consequences (liquidators and population) ≈ 60 people	250 000 people

Software and hardware systems (SHS)

- SHS for rescue units of the State Corporation "Rosatom" to assess the consequences of radiation accidents to the environment (air, water) and the population
- SHS with 3-D models to assess the effects of radiation accidents in complex industrial environment



Systems of emergency response and radiation monitoring in the RF regions



Territorial systems are created in the RF regions, where operational NPPs and NPPs under construction are located, to support local authorities functioning and to demonstrate safety of the NPP's operation
(system of emergency preparedness and independent radiation monitoring)

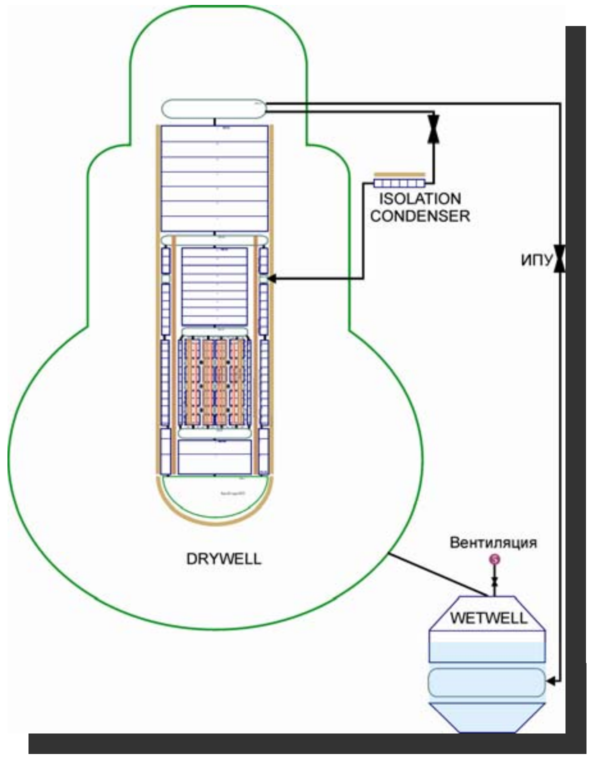
Scope of work:
- Establishment of crisis centers;
- Creation of territorial automated system of radiation monitoring;
- Development and equipment of software & technical systems;
- Creation of mobile laboratory facilities;
- Conduct of exercises and training.

Incident analysis for Fukushima-1 units 1-3 and spent fuel pool 4 (SOCRAT)

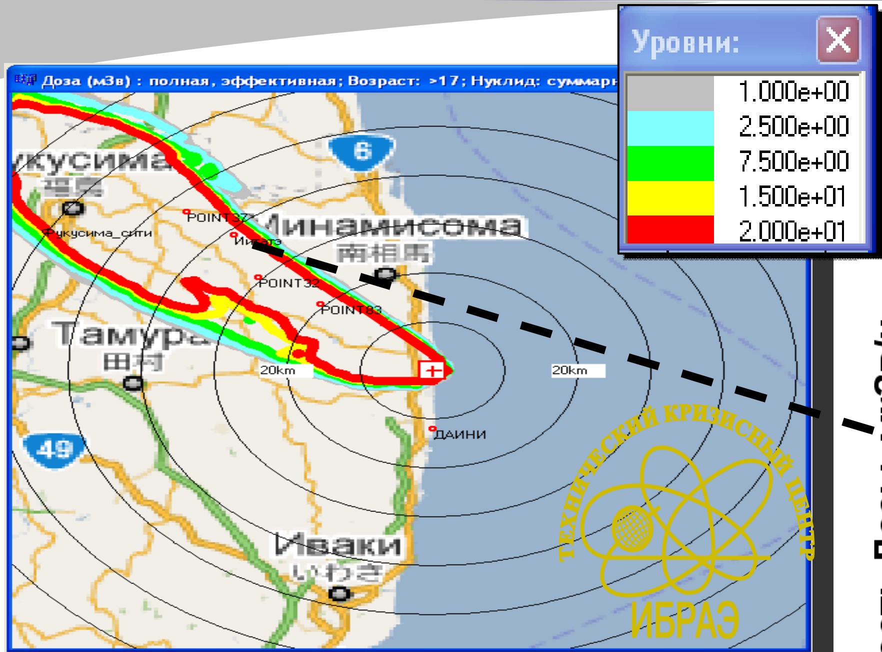
Without water cooling taken into account

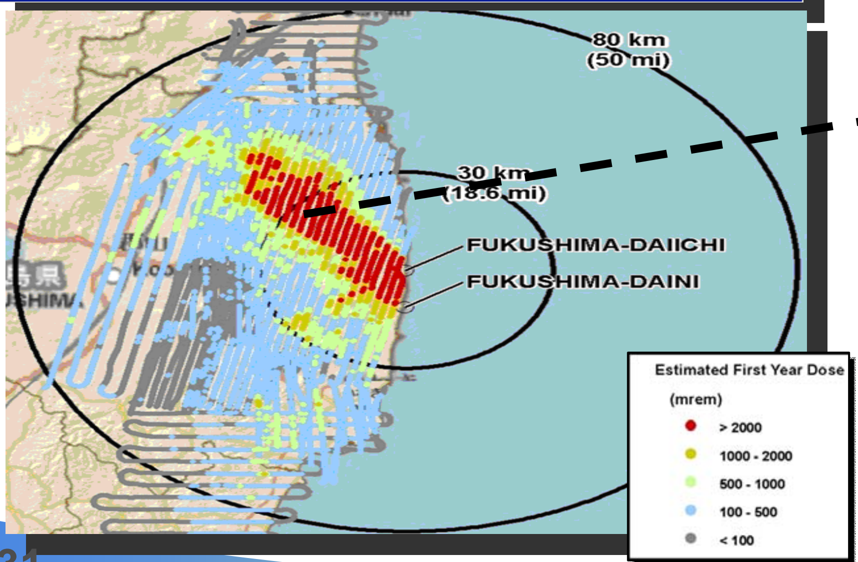
	Time (JAPAN) of explosion calculated (hydrogen for 1, 2, 4)	Time (JAPAN) of explosion actual (hydrogen for 1, 2, 4)
Unit 1	12.03 15:16	12.03 15:36
Unit 2	Pressure exceeding in the vessel 15.03 05:45	15.03 06:14
Unit 3	14.03 08:00	14.03 11:01
Unit 4 (fuel pool)	15.03. 4:00-05:00	15.03. 6:00

Reactor BWR/3 calculation model for SOCRAT code

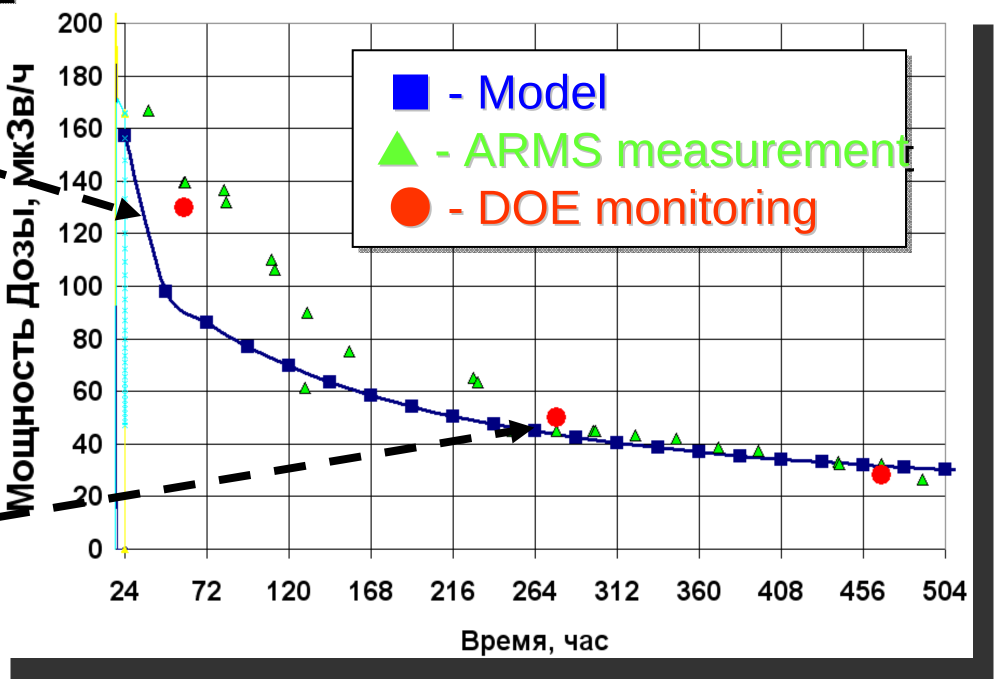


Atmosphere transfer modeling with account of detailed weather data in Japan





Modeling results and monitoring data



Fukushima experience

Territories and population in the areas with expected annual dose for population above 20 and 100 mSv after the Fukushima NPP accident

			Expected annual dose, mSv/year	
			> 20	> 100
In 20-km zone	Area, km^2	Total	327	101
		Populated	109	24
	Population, individuals		43 700	8750
Out 20-km zone	Area, km^2	Total	368	53
		Populated	84	11
	Population, individuals		16 300	4000
Total	Area, km^2	Total	695	154
		Populated	193	35
	Population, individuals		60 000	12 550

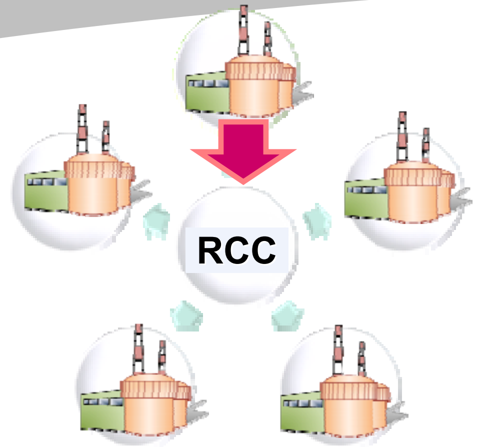
Fukushima experience

Recommendations on protective measures

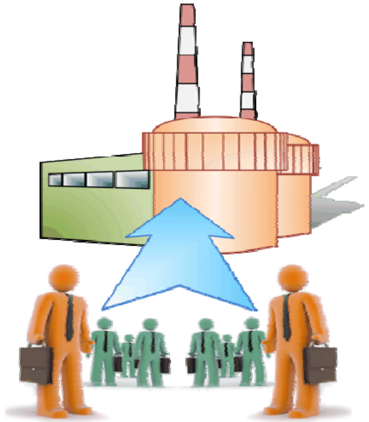
- For major part of the Japanese territory, the total radiation exposure doses for population for 20 days after the accident did not exceed 0.1 mSv. No protective measures are required.
- The total dose for population for 20 days in the most contaminated prefecture Ibaraki reached 0.6-1.0 mSv. Such prevention measure as control of milk and vegetable contamination for the first month is recommended.
- In the north-west trace out the boundary of 20-km area, the maximal doses for 20 days could reach 50 mSv. The expected dose for the first year without protection measure could reach total 150 mSv. Population evacuation is not justified. Deactivation, regular control over food and water contamination and some other measures are recommended.

Establishment of WANO Regional Crisis Center for NPPs operating VVER reactors

Goals of Establishing the Regional Crisis Center



1. Early notification and exchange of credible information between WANO MC Members in case of an accident or a safety important event occurred at NPP.



2. Establishing the Expert Community to provide real-time consultations and early engineering and technical support on request of an emergency NPP.

3. Establishing mechanisms for early provision of materials and technical resources as assistance of WANO MC Members on request of an emergency NPP.

What to do

- Detailed safety analysis of low probable scenarios with severe consequences.
- A global consensus on a set of accidents that should be considered and could be ignored.
- For severe, although low-probable accidents, protective measures should be included.
- The 100 times gap between radiation effect and regulation should be bridged.
- Public information should be an essential part of the atomic energy use.
- National technical centers should support emergency response to radiological incidents.

Conclusion

- Include into consideration the unlikely, though severe, accidents and eliminate them by deterministic methods;
- Be fully prepared for emergency response;
- Clear the rules for radiation protection;
- Provide the public involvement in the issues of radiation and nuclear technology safety.