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COMPARATIVE ANALYSIS OF THE DISPERSION MODELING AND DOSE PROJECTION RESULTS PERFORMED UNDER BARCO INTERNATIONAL PROJECT

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Abstract. Radiological assessments on zones to take protective actions in case of a nuclear or radiological emergency involve a series of real-time forecasts of radiological impact on the public at various distances from the release point, using actual weather or forecast data, information on the source term or facility status, and primary radiation monitoring data. This practice is implemented during the operation of emergency centers around the world in order to promptly report the occurrence and possible consequences of radiological accidents in the country and abroad in the event of a possible transboundary impact.

Since the Chernobyl disaster, a lot of emergency exercises, research programs and projects, in particular, benchmarking, have served as international platforms for improving modeling capacity in atmospheric dispersion. This activity is carried out both on the basis of past severe accidents with significant atmospheric releases and corresponding radiological consequences, and on the basis of specific conditional (hypothetical) events that are developed in accordance with the purpose of the study.

The paper is focused on the comparison results performed under the international project "Benchmarking on Assessment of Radiological Consequences" (BARCO) conducted in 2020-2021 between five technical support organizations – members of the European Technical Safety Organisations Network (ETSON). The work contains a short overview of relevant international activity conducted in the past, a description of the BARCO project and its objectives, a list of participants, project tasks, initial data (source term, meteorology, list of benchmarking quantities, approach to data exchange, codes used). The study presents some of comparative analysis results obtained via two techniques such as code-to-code analysis (CTCA) and matched-pair analysis (MPA). The results discussion concentrates on the overall recommendations for code users. Conclusions provide the main outputs of the project.

Key words: *BARCO, atmospheric dispersion modeling, dose projection, emergency preparedness and response, decision support system, matched-pair analysis.*

1. INTRODUCTION

The results of assessing the consequences of severe accidents at nuclear power plants (NPPs), the scale of which can reach transboundary character, serve as a substantial basis for taking protective actions and further analysis of the development of the radiological situation. Being one of the goals of emergency preparedness and response (EP&R) in mitigating the radiation consequences by devising recommendations for urgent countermeasures, forecasting the situation in most cases helps to achieve a significant reduction in public exposure levels, which, in turn, allows to avoid the emergence of deterministic effects and significantly reduce the risks of stochastic effects.

Along with the results of emergency monitoring by networks located around the NPP and throughout the country, forecasting and analysis of radiation consequences, an important stage in protecting the public even before the first results of radiation monitoring

55 are received, is the implementation of timely and justified countermeasures. The fast-
56 running tools such as RASCAL [1] and HotSpot [2] based on simple Gaussian plume model,
57 have been considered as reliable software to respond. However, more and more countries
58 give preference to modeling radiological consequences with complex real-time decision
59 support systems such as JRODOS [3], ARGOS [4], C3X [5], etc. In addition to the primary
60 application of these software systems - emergency response calculations - they are also
61 used for emergency preparedness and planning, quantitative and qualitative analysis of
62 possible emergency scenarios. This is primarily due to the wide range of capabilities of these
63 software tools both in terms of computational power and in terms of convenience of inputting
64 data, obtaining and analyzing assessment results.

65 Over the past 20 years, a significant contribution to the development of forecasting
66 tools was made by the US NRC's RAMP program [6], the FASTRUN project for
67 benchmarking of "fast" codes [7], European projects CONFIDENCE [8], PREPARE [9],
68 FASTNET [10], R2CA [11], certain projects in the SAFIR2022 research program [12], etc.
69 In order to highlight the overall picture of discrepancies in assessment results and to improve
70 harmonization of existing approaches to radiation consequences, benchmarking as a
71 component of improving calculation capability can be conducted within one country, like the
72 benchmarking emergency exercise ASEAN NPSR [13], or even within a single organization.

73 The full-scale exercises organized by the International Atomic Energy Agency (IAEA)
74 bear some elements of a comparative analysis of assessment tools as well. However, the
75 major focus of emergency exercises is on the qualitative comparisons of atmospheric
76 dispersion calculation results, and quantitative comparisons, if any, are conducted only for
77 a limited set of the results or a small number of spatial and temporal receptors.

78 **2. PROJECT DESCRIPTION**

79 BARCO (Benchmarking on Assessment of Radiological Consequences) is an
80 international project conducted in 2020-2021 with the aim to evaluate radiological
81 assessments' robustness within the context of the European Technical Safety Organisations
82 Network (ETSON) Members' relevant resources and capabilities. Technical Safety
83 Organisations (TSO) play an important role in nuclear safety and security. Their main task
84 is to provide competent, reliable and impartial technical expertise to the nuclear regulatory
85 body of their respective country. TSO strongly engages in furthering the state of science and
86 technology by conducting research and development, thus providing both the knowledge
87 and the analytic tools needed to ensure a high level of safety and security in the nuclear
88 field.

89 Representatives of five European Technical Support Organizations participated in the
90 project, namely:

- 91 – State Scientific and Technical Center for Nuclear and Radiation Safety (SSTC
92 NRS, Ukraine);
- 93 – National Agency for New Technologies, Energy and Sustainable Economic
94 Development (ENEA, Italy);
- 95 – Lithuanian Energy Institute (LEI, Lithuania);
- 96 – VTT Technical Research Centre of Finland Ltd, (VTT, Finland);
- 97 – Gesellschaft für Anlagen- und Reaktorsicherheit, GmbH (GRS, Germany).

98 The calculations were conducted by four of the above Institutions. The main role of the
99 fifth organization was to perform observing function. The participant provided independent

100 and overwhelming verification of the activities presented under tasks 1 and 2 of BARCO
101 project.

102 Within the scope of BARCO, analysis of radiological assessment robustness involved
103 an investigation on dispersion (deviations among results) of radiological consequences
104 assessment results collected from the different TSOs for single input data. One of the
105 project's objectives was to carry out the comparative analysis of the performance of EP&R
106 calculation codes used by ETSON Members for a general scenario, and to assess the
107 approaches to the use of modeling packages and methodologies with regard to modeling,
108 use of the databases, interpretation of results etc. The preliminary results of the project were
109 presented at the EUROSAFE Forum in 2021.

110 Under BARCO, the participants were expected to complete the task consisting of two
111 parts:

- 112 – assessment of the off-site consequences of an accident at the NPP on the territory
113 of Ukraine (Part 1),
- 114 – and modeling of the off-site consequences for the EU/ETSON countries due to
115 the same event (Part 2).

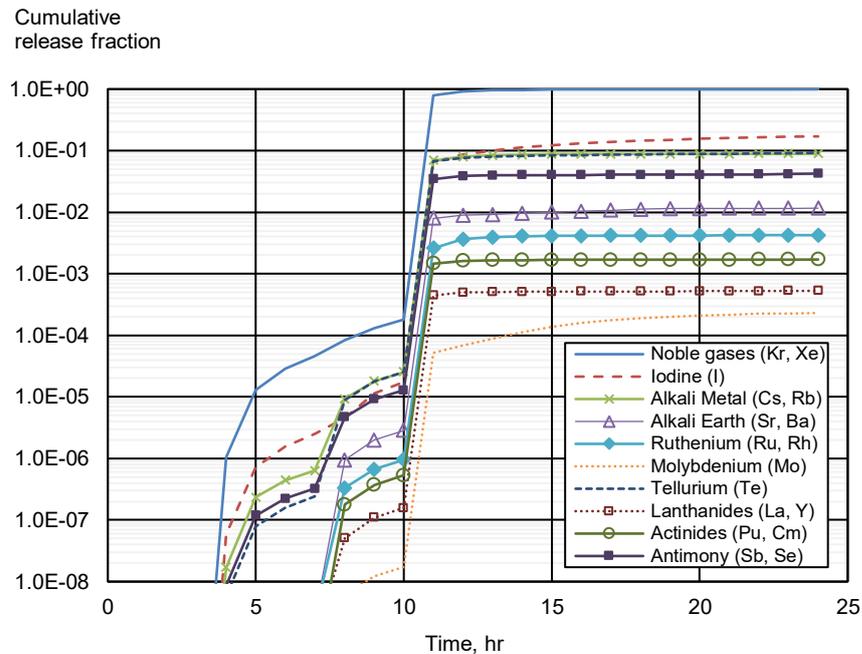
116 The participants were supposed to be using their routine atmospheric dispersion
117 modeling and dose projection tools, databases, calculation approaches, methods etc., but
118 a common single simulated scenario, specified in terms of source term, location and time of
119 the hypothetical event. In order to avoid a situation when, as a result of numerous refining
120 iterations, the data obtained has only very small differences between participants (which
121 cannot usually be the case during a real event), one of the conditions of benchmarking was
122 that all necessary calculations should be performed within 24 hours. This could be any 24
123 hours during the time periods assigned to perform the calculations.

124 **3. INITIAL DATA**

125 **3.1 Accident Scenario and Corresponding Source Term**

126 The simulated accident site “a NPP” is situated near Varash city. It is selected in
127 location of the real Rivne NPP which is the nearest Ukrainian NPP site to neighboring EU
128 countries. The shortest distance from the Rivne NPP to the border between Ukraine and
129 Poland is about 130 km, the nearest EU location is village Łuszków (Poland). “A NPP”
130 operates 2 WWER-440 and 2 WWER-1000 power units located in a region with the average
131 population density of about 4000 people per square kilometer.

132 According to the scenario, the simulated accident's development was based on a
133 realistic approach using MELCOR [14] calculation results in accordance with process
134 parameters of the reactor at full power in compliance with WWER-1000/V320 design.
135 Boundary conditions were set up in accordance with the design parameters of safety
136 systems and actions of emergency personnel. The scenario of large break loss of coolant
137 accident (LOCA) associated with total station blackout (SBO) was selected for WWER-1000
138 reactor. The severe accident scenario was selected as the worst with respect to accident
139 progression and it has an extremely low probability (approx. $5E-09$ year⁻¹) according to
140 probabilistic risk assessment (PRA).



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Figure 1 Cumulative release fractions for the selected severe accident (relative units)

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Information about fractions from core inventory released is presented in Figure 1 (time 0 corresponds to the end of the chain reaction in the reactor core). The transformation from the release fractions to the atmospheric release of nuclide-specific activities was performed using decision support system (DSS) JRODOS.

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3.2 Meteorology

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With the aim to select the date and time of the release, about two years of real archival data of numerical weather predictions (NWP) were analyzed using various online services, such as Earth [15], Windy [16], and NOAA HYSPLIT air trajectory model [17, 18]. As result, a release single date and time were selected that met the following requirements:

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- the release date should not be too old and the NWP data should be available to those participants who use them (storing meteorological data may require additional resources from participants; the size of data buffers of this kind can vary from organization to organization. In view of this, the selection of the date of the meteorological situation was focused on the most recent ones);
- air mass trajectories should lead to the transboundary transport of radioactive substances;
- meteorological conditions should be simple enough to allow the use of single-point weather data specific to the site of the release.

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Each participant was allowed to use their own meteorological data provider and data format.

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3.3 List of benchmarking quantities

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The list of benchmarking quantities was developed based on the chronological aspects of plume configuration (transport and spread timing), operational intervention levels (OILs) developed and published by IAEA in EPR-NPP-OILs (2017) [19], generic criteria for urgent protective actions, generic criteria for early protective actions and other

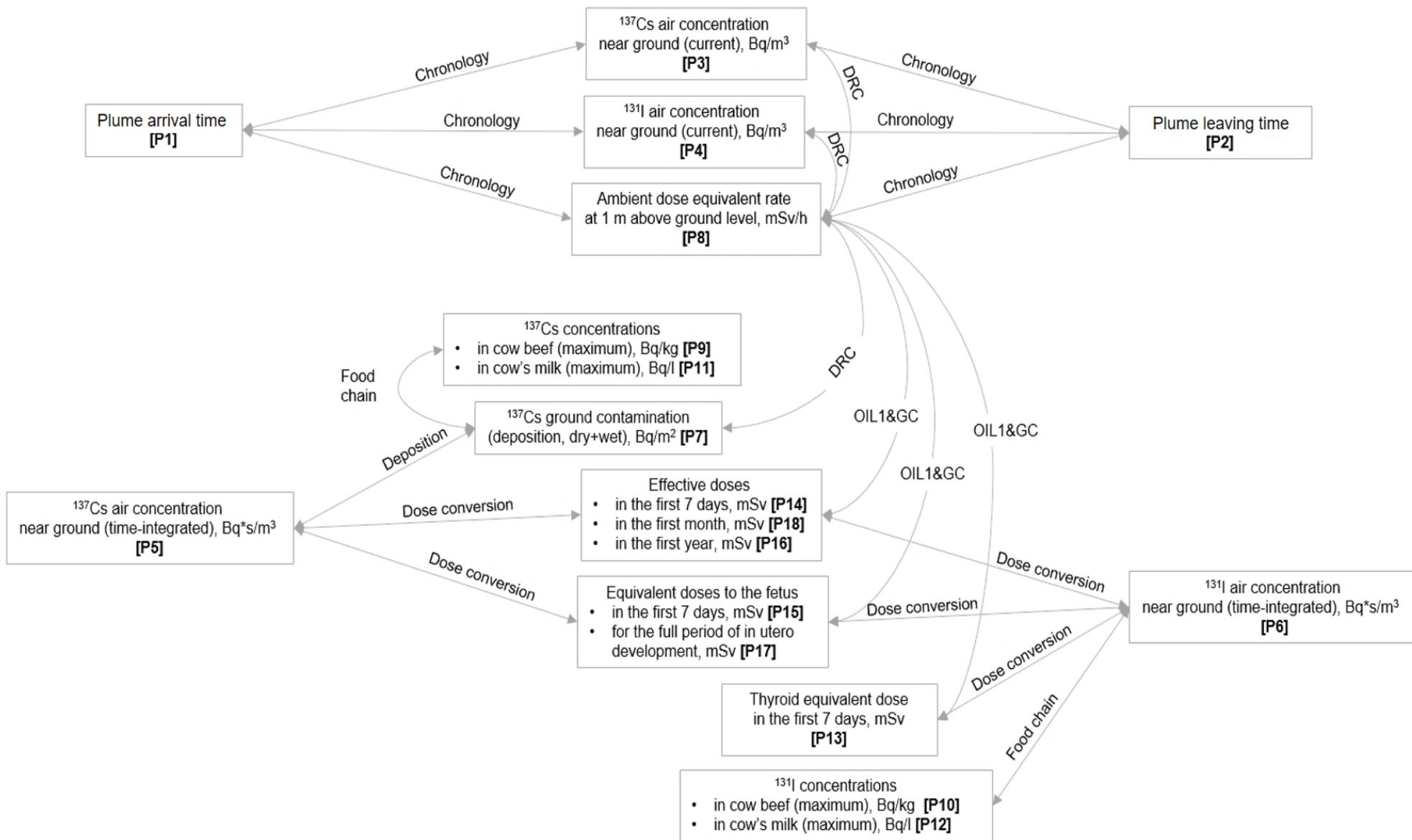


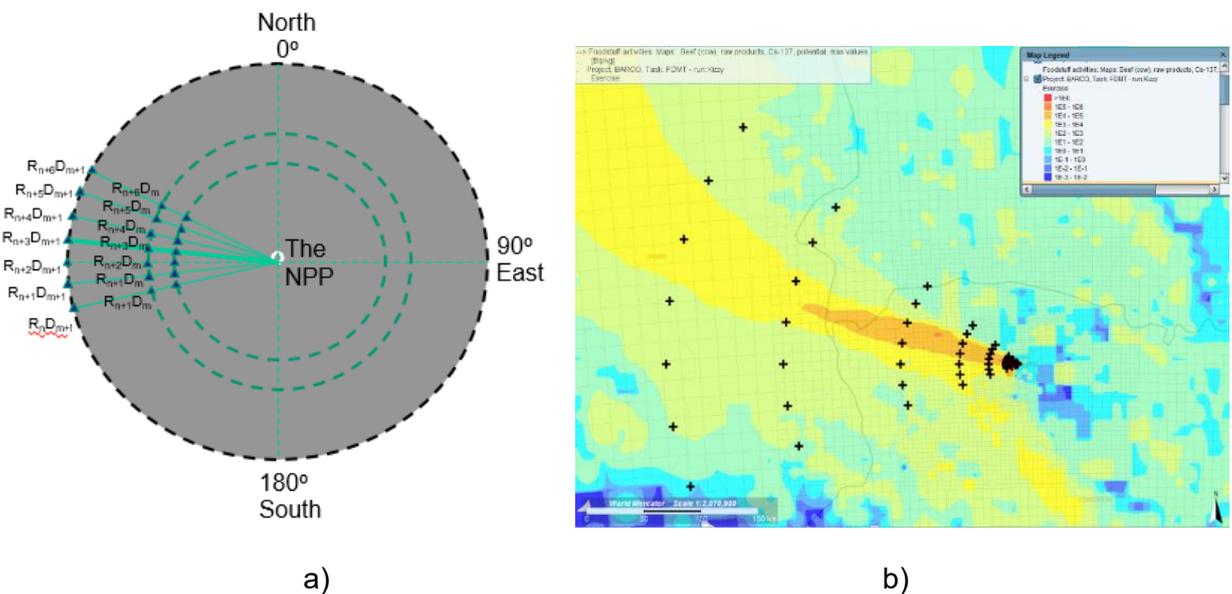
Figure 2 Scheme of relations between benchmarking quantities

170 response actions for longer term medical actions to detect and to effectively treat
 171 radiation induced health effects, as recommended in IAEA's GSR P.7 [20]. A general
 172 scheme of the quantities in the calculation branches is presented in Figure 2. It shows
 173 relations between benchmarking results, considering in frame of code-to-code analysis
 174 (CTCA) and matched-pair analysis (MPA). Meanings of presented effective and equivalent
 175 doses, operational intervention level OIL1 corresponds to Generic Criteria (GC) of
 176 GSR Part 7 [20], and EPR NPP OILs (2017) [19]. The link DRC (dose rate conversion) point
 177 to transmission from ground concentrations to dose rate.

178 **3.4 Format of the results**

179 Based on the preliminary calculation, a special benchmarking grid for Part 1 of the
 180 benchmarking (Figure 3) was developed to cover a spatial area of interest and all possible
 181 angular deviations related to the results obtained by the participants. The grid was built in
 182 polar coordinate system considering TECDOC-955 [21] reference distances from the
 183 release point. Angular distribution of the grid was set as a 60°-sector with the resolution
 184 of 10°. It allowed the participants to analyze result distributions over radial lines, equal
 185 distances (single-distance section) and time-dependent results (dose rate, current air
 186 concentration of nuclide, etc.) for each spatial point. Regarding the source term time-
 187 resolution, it was appropriate to use 1-hr time step for time-dependent results.

188 For the far range modeling in the Part 2 of benchmarking activity, the concept of
 189 100 km-step circles around the release point was applied. Participants provided the
 190 maximum values of each quantity over each circle as a function of distance steps



194 **Figure 3** Results grid: General scheme (a) and GIS-shapefile integrated to JRODOS system (b)

195 **3.5 Calculation Tools Used by Participants**

196 The BARCO Project envisaged the use of any routine tools for the assessment of the
 197 radiological consequences of the emergency by the participants.

198 The decision support system JRODOS [3] provides consistent and comprehensive
 199 information on the radiological situation development, the extent, benefits and drawbacks of
 200 applied emergency actions and countermeasures, and methodological support for taking

201 decisions on emergency response strategies. The main users of the system are those
 202 responsible at the local, regional, national and international levels for off-site emergency
 203 management. JRODOS has the most diverse collection of dispersion models incorporated
 204 into software: Gaussian puff (RIMPUFF), Lagrangian (DIPLOT and LASAT), Eulerian
 205 (MATCH). Additional decision aiding components can facilitate the ranking and selection of
 206 alternative options using decision analysis procedures.

207 ARANO [22] is a domestic instrument of VTT developed in 1970's and initially used for
 208 nuclear power plant siting studies. Today, the code is used to estimate the effectiveness of
 209 different countermeasures. Especially in recent years, ARANO was used by VTT to support
 210 the Finnish Radiation and Nuclear Safety Authority (STUK – Säteilyturvakeskus) in various
 211 safety assessments for constructing new power plants, dismantling a research reactor, as
 212 well as for a spent fuel disposal site.

213 VALMA [23] is a dispersion and dose assessment code for accidental atmospheric
 214 radioactive releases developed at VTT in late 1990's. Its main purpose was to serve as an
 215 emergency preparedness tool for STUK. In such use, it is essential to produce predictions
 216 of concentrations, depositions, dose rates and doses in a reasonably short time to enable
 217 possible rapid countermeasures. Taking into account its limitations, VALMA was made
 218 flexible enough to work with many kinds of weather data, starting from single-point
 219 measurements at the weather mast of an NPP (or several masts) and ending with Monte
 220 Carlo particles (even a limited number) that can be calculated, based on NWP models, with
 221 the SILAM dispersion model at FMI (Finnish Meteorological Institute).

222 The FLEXPART model is used for a wide range of simulations related to the transport
 223 of various types of aerosols in atmospheric air; the model is not limited to radionuclides. The
 224 first version of the Lagrangian atmospheric dispersion model FLEXible PARTicle
 225 (FLEXPART [24]) was developed in the mid-90s at the Norwegian Institute for Air Research
 226 to simulate the long-range and mesoscale aerosol dispersion from point sources, in
 227 particular NPPs.

228 Table 1 shows the list of calculation resources and specific data used by each
 229 participant regarding above mentioned codes.

230 **Table 1** List of calculation resources and specific data used

Participant/resources		Part 1 (modelling up to 300 km)	Part 2 (far range modelling in transboundary context)
Participant 1	Software	JRODOS	JRODOS
	Atmospheric dispersion model	LASAT	MATCH
	Type of meteorology (provider)	NWP – WRF results [25], 0.15-deg and 1-hr resolution (national service - Ukrainian Hydrometeorological Center)	NWP – GRIB 0.5-deg and 3-hr resolution (national service – Ukrainian Hydrometeorological Center)
	Calculation grid	400 km	Limited to NWP data
	Size of the nearest calculation cell to the release point	1.0 x 1.0 km	35.3 x 55.7 km
	Benchmarking quantities	P1-P14, P16, P18	P1, P2, P5-P7
Participant 2	Software	JRODOS	JRODOS
	Atmospheric dispersion model	RIMPUFF	RIMPUFF
	Type of meteorology (provider)	single-point weather data (on-site)	NWP - GRIB 0.5-deg and 3-hr resolution (Global Forecasting System)
	Calculation grid	800 km	800 km

Participant/resources		Part 1 (modelling up to 300 km)	Part 2 (far range modelling in transboundary context)
	Size of the nearest calculation cell to the release point	2 x 2 km	2 x 2 km
	Benchmarking quantities	P1- P18	P1, P2, P5-P7, P13, P14, P17
Participant 3	Software	JRODOS / FLEXPART	JRODOS / FLEXPART
	Atmospheric dispersion model	RIMPUFF / FLEXPART	MATCH / FLEXPART
	Type of meteorology (provider)	NWP – ECMWF [26] (HRES model), 0.25-deg and 3-hr resolution / NWP - ECMWF [26] (HRES model), 0.25-deg and 3-hr resolution	NWP - GRIB 0.25-deg and 3-hr resolution (NOAA-GFS) / NWP - ECMWF (HRES model), 0.25-deg and 3-hr resolution
	Calculation grid	400 km / Limited to NWP data	Limited to NWP data
	Size of the nearest calculation cell to the release point	1 x 1 km / 0.25 deg.	0.25 deg. / 0.25 deg.
	Benchmarking quantities	P1-P14, P16, P18 / P3-P7	P1, P2, P5-P7, P13 / P5-P7, P13
Participant 4	Software	ARANO / VALMA	VALMA
	Atmospheric dispersion model	Gaussian / Lagrangian	Lagrangian
	Type of meteorology (provider)	single-point weather data (on-site) / ECMWF [26] with 0.15-deg resolution, accessed by FMI / SILAM model	NWP - ECMWF [26] with 0.15-deg resolution, accessed by FMI (SILAM model)
	Calculation grid	Limited to 60 hrs of dispersion / Limited to 48 hrs of dispersion	Limited to 48 hrs of dispersion
	Size of the nearest calculation cell to the release point	- / -	-
	Benchmarking quantities	P13, P14, P16, P18 / P1-P8, P13, P14, P16, P18	P1-P8, P13, P14, P16, P18

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4 METHOD OF ANALYSIS

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With the aim of looking at deviations and investigating the relations between results, a standard technique of the code-to-code analysis (CTCA) was applied. In addition, the deliverables of the project contained the results of calculations presented as curves over distances and scatter plots for each pair of codes based on numerical arrays provided by all participants. Such graphic information was provided for each benchmarking quantity and allowed to highlight the similarities and deviations. Additionally, marking points in scatter plots demonstrated convergence degree over distance (i.e. higher concentrations relate to near distances, lower concentrations – to far ones).

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A matched-pair analysis (MPA) was applied as the second technique and turned out to be an effective tool to identify the links of the result tree that lead to deviations between results obtained in the frame of Part 1. Matched pairs were selected on the scheme of relations between benchmarking quantities (Figure 2) and cover all 18 benchmarking quantities by 6 factors, namely:

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- plume dynamics,
- deposition,
- dose rate conversion,

- 249 – dose conversion,
- 250 – food chain,
- 251 – relation between operational intervention level OIL1 (gamma dose rate) and
- 252 IAEA's Generic Criteria (1-week projected doses).

253 All relations considered in such analysis can be regarded to track qualitatively due to
254 the limited list of benchmarking quantities. It is supposed that the presented pair correlations
255 can reflect the general behavior of a participant's results with reference to the rest of the
256 results.

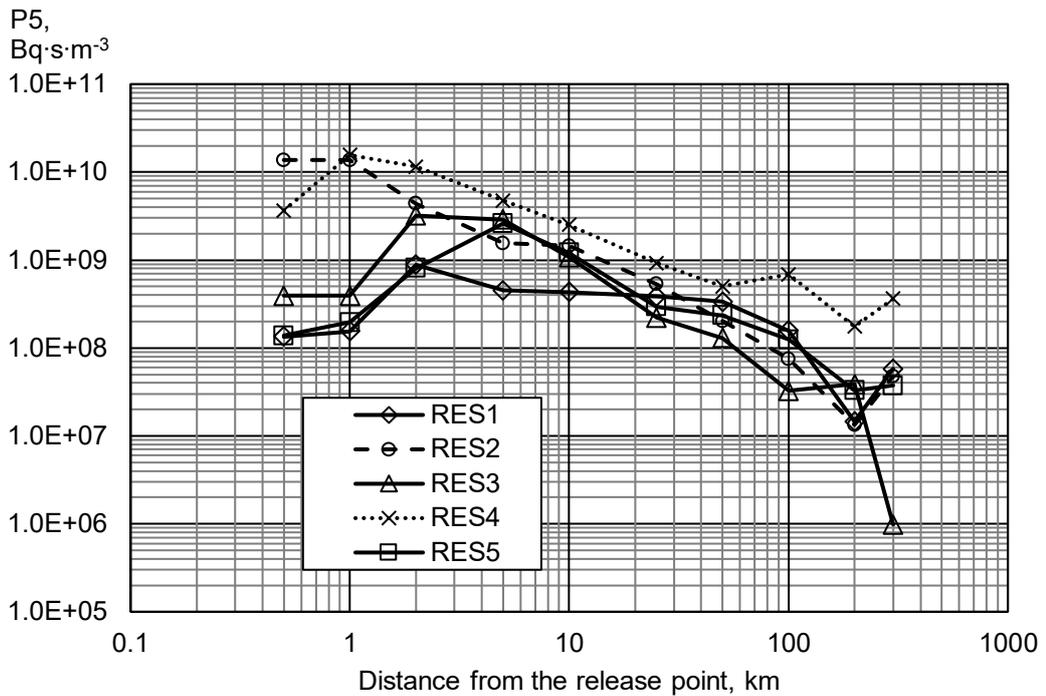
257 **5 RESULTS AND DISCUSSION**

258 In Part 1 of benchmarking activity, Gaussian dispersion modeling as well as advanced
259 Lagrangian dispersion modeling were presented. Advanced dispersion models are more
260 sophisticated than Gaussian-plume models, and aim at producing more realistic results.
261 Even so, results from advanced models should not be automatically assumed to be better
262 than those obtained from Gaussian-plume models. The different categories of atmospheric
263 dispersion models are based on different assumptions and can be applicable to different
264 situations. Gaussian-plume model is based on the assumption of a spatially uniform wind
265 velocity field. A Lagrangian particle model on the other hand is applicable for a spatially
266 variable (in all 3 dimensions) wind velocity field. For instance, in case of JRODOS system,
267 RIMPUFF model cannot account for variations of wind speed and direction in height,
268 whereas DIPCOT and LASAT can. Hence, the dispersion models in LSMC of JRODOS that
269 can actually fully use a 3-dimensional wind velocity field are DIPCOT and LASAT.

270 **5.1 Part 1**

271 The code-to-code analysis demonstrates consistent correlations among participants'
272 results in a range of 5-50 km (Figures 4, 5). Instead of concentrations, the correlations are
273 visible in dose projection results such as effective doses or thyroid doses (Figure 5).
274 Obviously, in case of diversity in types of models, some typical patterns can be observed. It
275 refers to high degree of deviations in near and far-ranges, and relative convergence in the
276 middle range. In some cases, Gaussian models (curve RES5, Figure 5) may be expected
277 to perform better near the source, whereas they may fail at distances of more than a few
278 tens of kilometers. On the other hand, NWP-based Lagrangian dispersion models may be
279 quite reliable up to hundreds of kilometers.

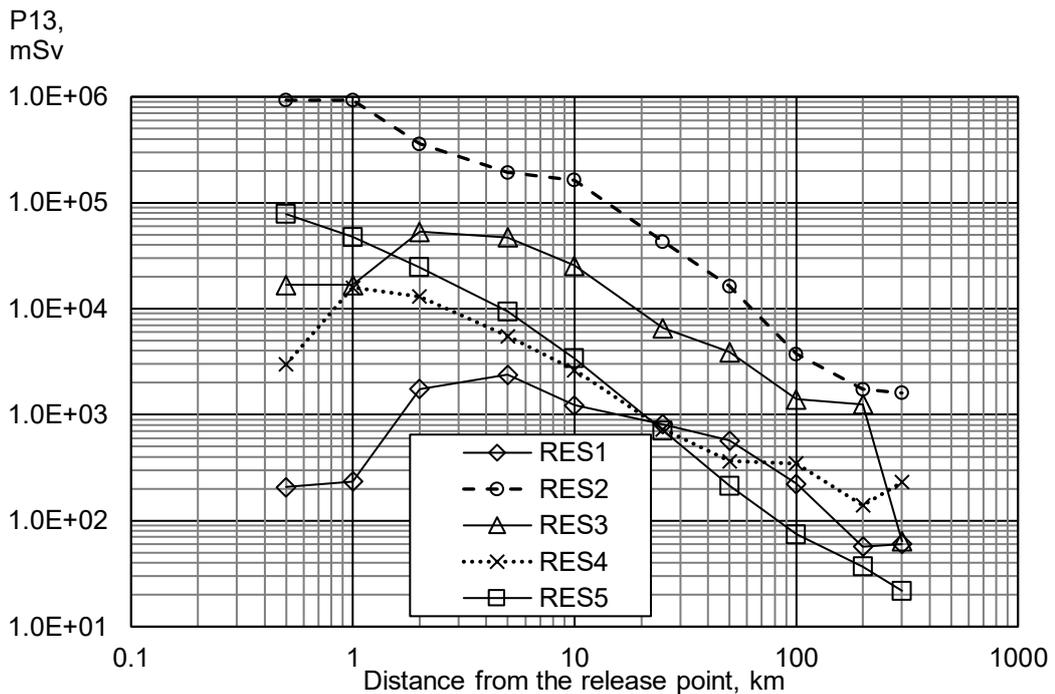
280 The neutral markers for participants' results were chosen (from RES1 to RES5) to not
281 establish any links to certain Institutions.



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Figure 4 CTCA on quantity P5 (¹³⁷Cs air concentrations near ground, time-integrated)



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Figure 5 CTCA on quantity P13 (thyroid equivalent dose in the first 7 days)

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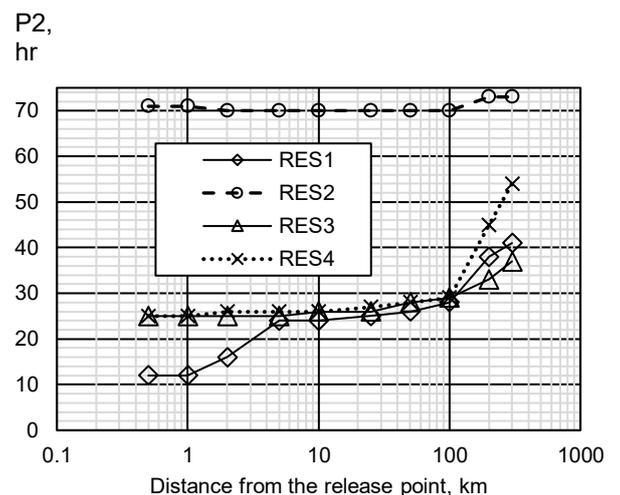
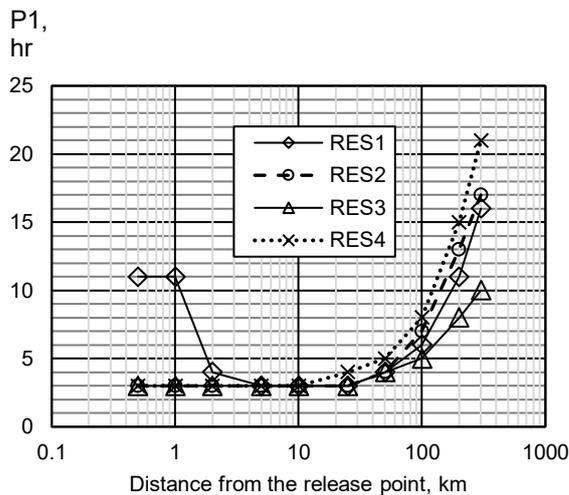
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Chronological quantities of the plume dynamics relate to time such as plume arrival time or plume leaving time. These quantities depend on pre-set thresholds in instantaneous results in dose projection tools such as current activity of radionuclide(s) in the near ground air or dose rate. In some cases, the user can face abnormal behavior in such quantities as plume arrival and leaving times due to the numerical features of the specific software. For instance, plume leaving time, according to some results, brings non-physical values as a result of still remaining concentration (curve RES2, Figure 6b). The user of the software should in all cases be aware of the variable(s) as well as the threshold value(s) used in the system at hand for estimating the plume arrival and leaving times.



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Figure 6 CTCA on quantities P1 and P2: Plume arrival (a) and leaving (b) time (Part 1)

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Such effects can be particularly reflected by the models of a representative sample of tracer particles utilizing a random walk process (Lagrangian simulation) and/or unstable meteorological conditions. This is an individual issue for a particular atmospheric dispersion model and a particular tool. User guide information or contact with the developers can help to find out the thresholds when software responds to concentrations or dose rate values in the context of plume arrival/leaving information. To avoid presenting clearly non-physical results about plume arrival, it would probably be safest that the user looks directly at the concentration and plume dose rate prediction time series at the receptor point.

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When OILs are implemented in a dose projection tool, it is important to pay attention to relations between them and generic criteria calculated. Generally, this issue addresses procedures used to derive the OIL values. International practice, e.g. HERCA-WENRA approach [27], demonstrates a tendency to harmonization of criteria to take a protection action in the off-site and transboundary consequences context. However, it is important to notice that models and databases used in the derivation of OILs should not be neglected in this case. Usually, the OILs are defined for directly measurable quantities, which are also more primary (i.e., calculated first) in the internal calculations of the simulation model, whereas generic criteria are defined in terms of accumulated doses or dose commitments, which are usually the final calculations inside the simulation chain, and so dependent on still more influencing factors.

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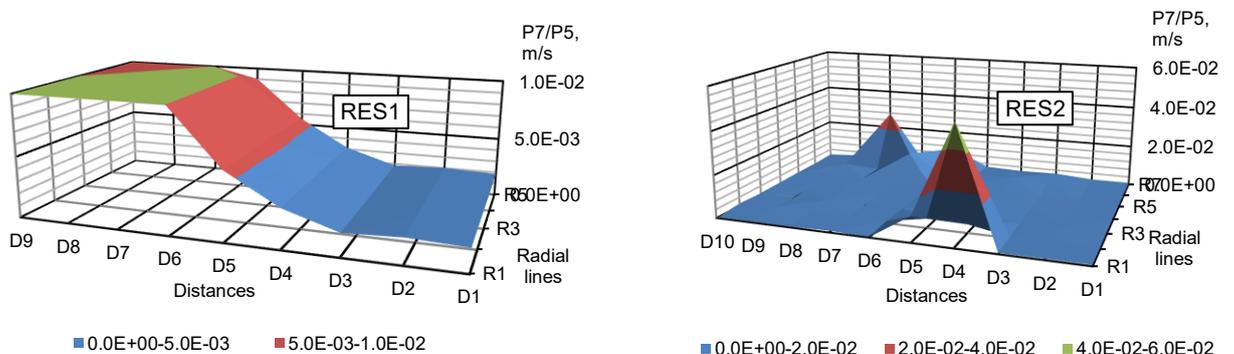
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Even within a single atmospheric dispersion model, some dose projection tools allow obtaining the results on different spatial and temporal scales. Scale selection depends on the distances of interest. In Part 1 of BARCO project 300-km benchmarking grid was applied. In some cases, far- or middle-scale selection could lead to some loss in results resolution due to averaging in the near range. For example, participants used RIMPUFF atmospheric dispersion models, but in the first case on 800 km results grid, in the second case – on 400 km results grid. This choice determines automatically the resolution of the cells near the emission point in JRODOS and the user has no opportunity to change this feature. This, in turn, impacts the near range results resolution and averaging. Sensitivity to the grid resolution should be considered for further studies of its impact on the model's output. A useful feature in a dose projection tool would be to have the results grid refined near the source where the quantities' values usually change most rapidly, with smaller grid cells providing better resolution. Such a feature is common in CFD tools.

330 Code-to-code analysis shows that meteorological data can lead to significant
 331 deviations in the results of atmospheric dispersion modeling at 20 km from the release
 332 source. At least under BARCO project the meteorological data such as numerical weather
 333 predictions or single-point data used by participants were not compared, or verified against
 334 reanalysis meteorological data. Undeniably, this affected the general picture of the
 335 deviations in results. Moreover, correct data transmission in the used software is an
 336 important step in radiological consequence assessment. In the interface SILAM-to-VALMA,
 337 some data points very close to the source (< 3 km) could be missed because of human error
 338 (automatic interface exists, but was not used in this case). This affected the short-range
 339 results up to approximately 3 km, but had no effect on larger distances. In such cases data
 340 transmission should be automated reliably using dedicated programs (e.g. in JRODOS
 341 system a NWP-data launcher is implemented).

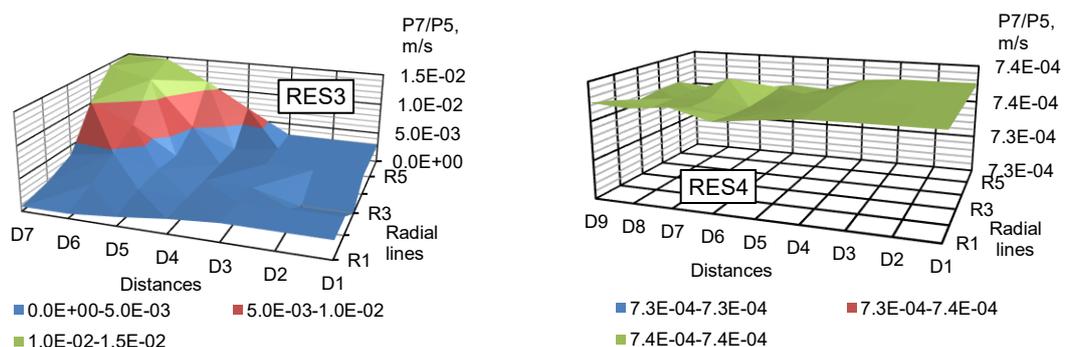
342 At further stages of result post-processing, matched pair analysis has been applied to
 343 all result branches presented in Figure 2. It has been used to screen for potential deviations
 344 in the results obtained by each participant. In the practice of benchmarking, MPA can be
 345 applied as an effective tool to define the calculation step where the main contribution to the
 346 general deviation of the result is rising and can be observed. The tool allows the participants
 347 to find out a probable reason for the deviation and point out the stage on which the
 348 differences grow a lot.

349 Using a specific ratio between time-integrated ^{137}Cs concentration in the near ground
 350 air (P5) and ground contamination by ^{137}Cs (P7), dry and wet deposition velocity was
 351 analyzed (Figure 7). The results of the analysis highlight the character of deposition pattern
 352 in the results of all participants. Such quantity as ground contamination influence long term
 353 doses. Therefore, pre-set deposition velocity for a particular physical or chemical group of
 354 radionuclides with meteorological data can significantly affect e.g. 1-year effective dose.
 355 This is only one of the specific ratios, obtained in the BARCO project, allowing us to observe
 356 in which distance or radial line, deviation is significant.



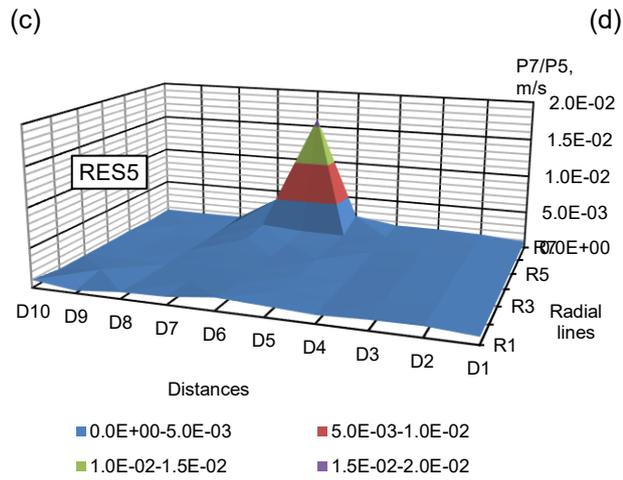
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(e)

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Figure 7 MPA on the specific ratio P7/P5: ¹³⁷Cs ground deposition to ¹³⁷Cs air contamination near ground from 5 result packages (a-e)

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According to MPA, as well as CTCA, the most consistent results were obtained in the branch of food chain in comparison to other branches of calculation. The character of the specific ratio presented in corresponding matched pairs is homogeneous. Such values as the concentrations in cow's beef or cow's milk are acceptably close among participants' results. However, attention should be paid to the distribution coefficients used. These parameters can depend on some specific data in the databases used (data on soil type or radio-ecological region). Concentrations in various foods are usually affected by the transfer coefficients that were used in the underlying biosphere transfer / food chain model.

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Dose rate conversion and dose conversion values show significant deviations in dose models results. The differences observed in dispersion modeling lead to differences in dose projection, especially at the distances of up to 10 km. Deviations in dose conversion factors and models influence doses additionally. Regarding to an effective dose in the first 7 days the results demonstrate deviation of several orders of magnitude in the 10 km range and around one order in longer distances. More significant deviations were observed in thyroid doses. Dose rate conversion and dose conversion are one of the main steps where uncertainties are increased in comparison with the previous steps of calculation (atmospheric dispersion and deposition). Usually available tabulated values of e.g., inhalation dose conversion factors (Sv/Bq) have the choices of slow / moderate / fast absorption from the lungs, which can make a big difference in the dose commitment received per activity inhaled into the lungs (ICRP 119 [27]). Such a choice could be different in different dose calculation models.

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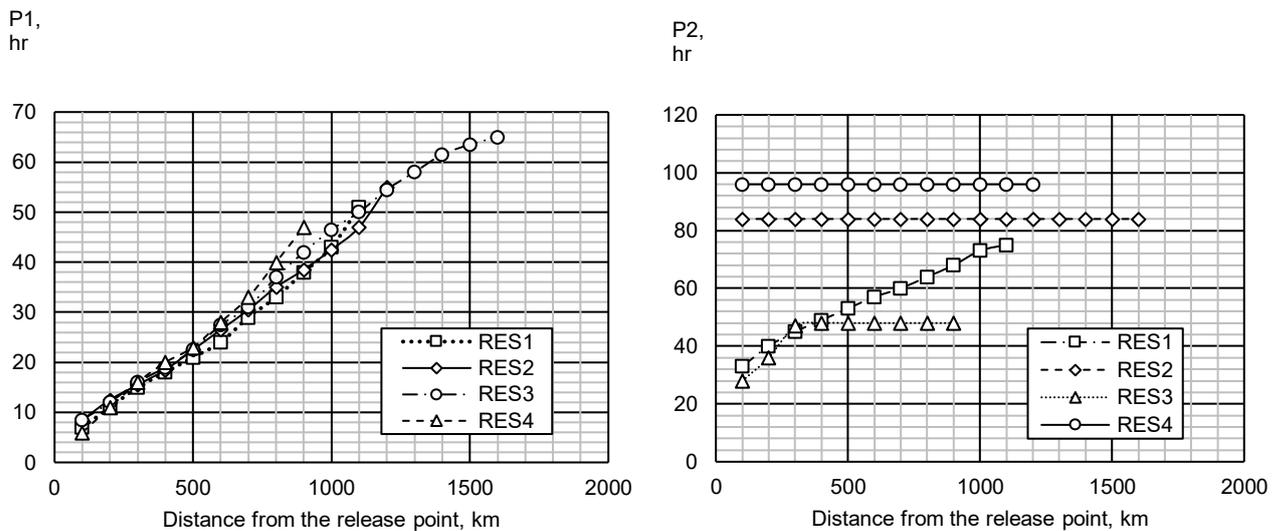
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With regard to the scope of results, only one participant provided the values for an equivalent dose to the fetus in the first 7 days, and an equivalent dose to the fetus for the full period of in utero development. Any assessment can be requested by other countries who have criteria on fetus doses (e.g., through Response and Assistance Network). This gap in major results is related to corresponding limitations in radiological consequences assessment resources. Many offsite dose tools do not have the option to consider the unborn fetus directly in the simulation. Fetus doses can be roughly assessed using backup algorithms referring to internal calculation approaches of an emergency center. Existing capabilities and resources of participants in this respect can be extended using simplified expressions, e.g. in part of branch "time-integrated air concentration near ground – fetus dose".

5.2 Part 2

The scope and structure of the reports provided by all participants under Part 2 (far-range modeling) are quite comprehensive and generally reflect the main requirements for the necessary information in case of an emergency.

In the transboundary assessment plume arrival time can be one of the most important quantities. It primarily depends on the numerical weather prediction data that are applied on the global scale. The results show acceptable convergence among all participants. However, more deviations (2-4 hours) appear starting from 600 km (Figure 8). Results RES4 demonstrate plume deceleration from 500 km (cloud leaving times may possibly contain 'artifacts' caused by the temporal grid range).



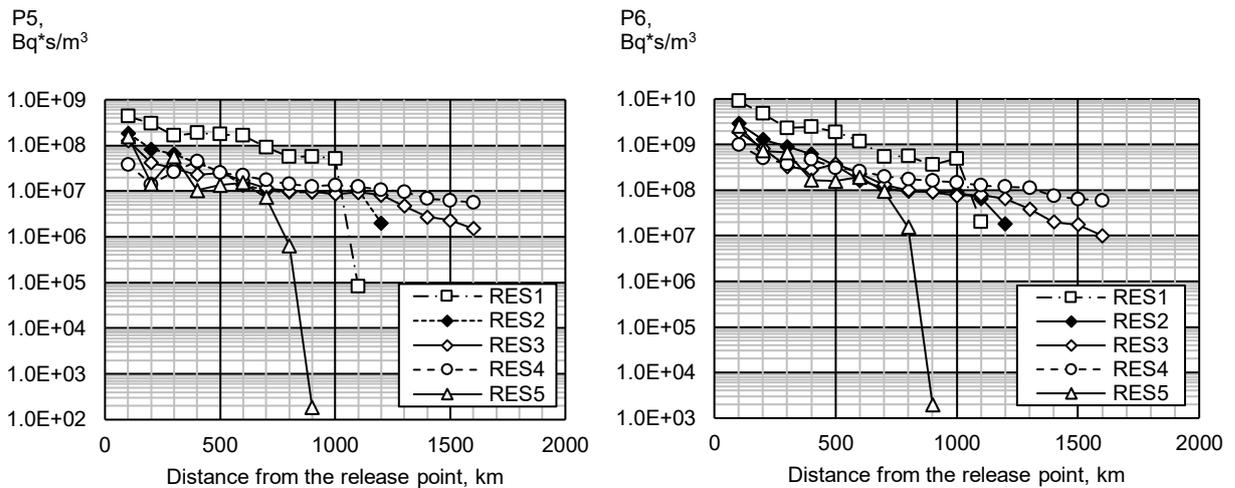
a) b)
Figure 8 CTCA on quantities P1 and P2: plume arrival (a) and leaving time (b) (Part 2)

Each participant presented plume leaving times in Part 2 in a different way. Two participants provided the values corresponding to the end of atmospheric dispersion modeling (96 and 84 hours – lines RES4 and RES2 respectively). Dispersion is not finished, because in these cases the duration of prognosis is limited by the meteorological data set. Other participants presented data allowing evaluation of a physical plume leaving time over distances. Results RES3 (Figure 8b) indicate that the dispersion process continues at distances from 400 to 900 km and the plume leaving time equals the end of the prognosis.

Both software options and modeling features can lead to incorrect result interpretation. Attention should be paid to radionuclides concentrations associated with the plume arrival or leaving time. Application of different assessment tools or atmospheric dispersion models has a minor contribution in chronological quantities such as plume arrival or leaving time. From this point of view numerical weather prediction data create more uncertainties in modeling results. A detailed analysis of chronological quantities requires a dedicated comparison among weather forecasting models.

Air concentrations near ground (time-integrated) characterize atmospheric dispersion. The values of time-integrated air concentrations provided by participants (Figure 9) are within one order of magnitude at the distance of up to 600-700 km. Some differences can

428 be explained by the use of different atmospheric dispersion models and topography. Results
 429 of one participant drop after 800 km because of end of calculation grid.



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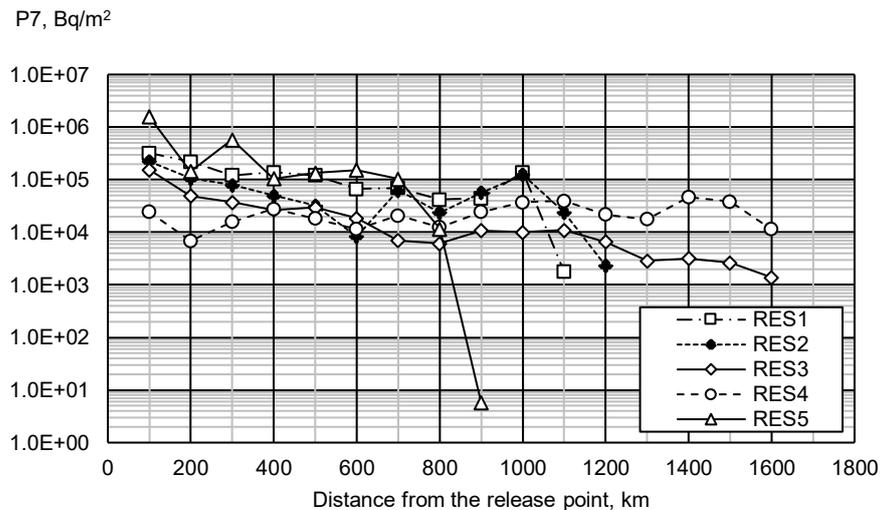
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a) b)
Figure 9 CTCA on quantities P5 and P6: ^{137}Cs (a) and ^{131}I (b) air concentration near ground (time-integrated)

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Total deposition of some dose-producing radionuclides can occur due to precipitations above the calculation grid. ^{137}Cs ground contamination results are presented in Figure 10.



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Figure 10 CTCA on quantity P7: ^{137}Cs ground contamination (deposition, dry&wet)

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Some deviations between the results on deposition velocity for aerosols defined as the ratio between time integrated air concentration and ground contamination are also observed, and depend on the default deposition velocity constants for aerosols, molecular and organic iodines and precipitation intensity in the numerical weather data.

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Some results highlight a possibly non-physical behavior near the calculation domain boundaries (Figure 11) that could be numerically induced. Generally speaking, plume transit or residence time over a given area is limited by the duration of the prognosis. It is possible that the plume does not reach the edge of the computational grid, or reaches it only at the final steps of the prognosis. This effect can lead to artificially low values in doses.

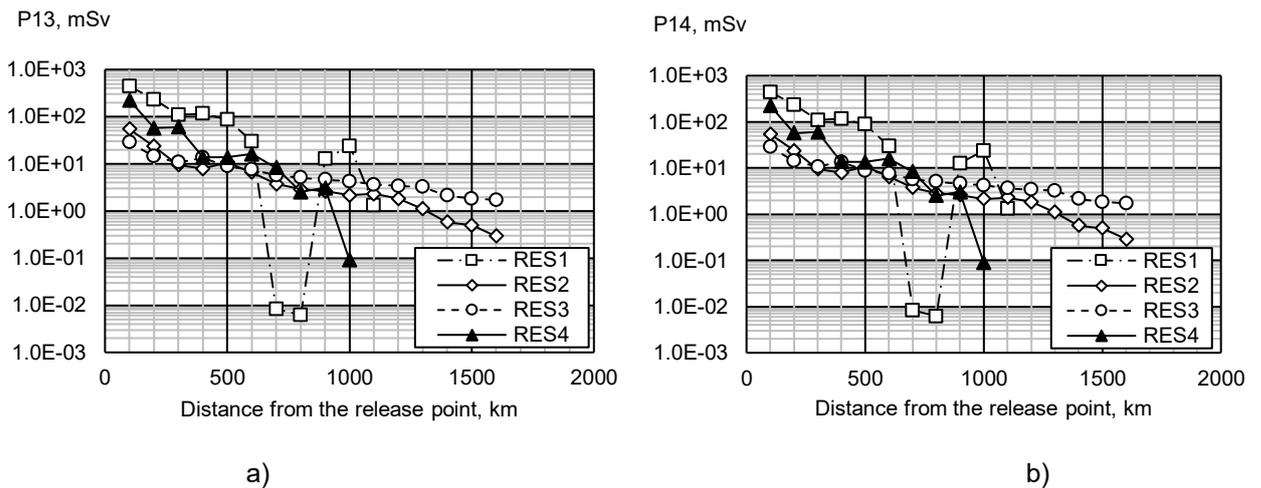


Figure 11 CTCA on quantities P13 and P14: thyroid equivalent (a) and effective (b) dose in the first 7 days

Gaps in thyroid and effective doses in one of result packages (RES1, Figure 11) at the distances of 600-800 km (above the sea surface) and high values at further distances can probably relate to PostgreSQL DB used for JRODOS calculation above the sea surface and increasing precipitation in the end of prognosis.

Dose models are rarely or only partially available in long-distance modeling calculation tools, e.g., the MATCH model implemented in JRODOS system or FLEXPART which can be used for limited exposure pathways in dose assessments while additional quantities must be computed from time-integrated atmospheric dispersion results. In fact, time-integrated air concentration and ground contamination can be used as primary data to derive effective and equivalent doses in the transboundary context, but then those quantities should be separately available for sufficiently many important nuclides. Clear and approved procedures should be developed to adapt or customize existing tools for a complete dose assessment in far-range.

With the aim to optimize the calculation process, spatial limitations in numerical weather prediction data used for the far-range calculation should correlate to the duration of meteorology data set. It can allow to avoid overloading of the assessment tool and save computational time. At the same time averaging in the computational cells associated with far-range modeling creates additional uncertainties in the distances from the release point to several hundred kilometers.

5.3 Summary of the benchmarking

Results presented in the article are only a part of the whole scope of the results provided in frame of the BARCO project. Based on analysis of whole data set the recommendations were provided. However, the participants were not only comparing the physical models, but also the overall response procedure, using the models (including choice of weather model, dispersion model, dose projection, etc.). As the main BARCO output, the recommendations for codes' users derived from the project are the following:

- a. Atmospheric dispersion and/or dose projection tools, and related databases should be adapted so as to take into account methodological approaches, past experience and best practice in modeling, requirements of national and international standards and guidelines; It would be good to have adjustment options available at user level (and not only fixed by the developer);

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- b. In addition to code user guides, the development of internal procedures on different types of calculations that can be used in emergency response conditions seems to be feasible to save calculation time (including far-range modeling). For new users or someone who has not used the code for a long time, a step-by-step instruction (depending on code) would be recommended. Activity on the development of such guidelines should be supported by code developers. The instruction set should include both a 'basic' version to have first results quickly in an emergency, and a more advanced version taking more time but allowing for more accurate results.
 - c. Default databases can be supplemented by a set of pre-defined source terms (for combinations of plant type and assumed accident sequence) derived from a practical scientific activity on radiological consequences based on available sources (such as works under specified international projects, IAEA publications emergency exercises, development or review of NPP safety analysis reports) with the aim to avoiding additional uncertainties in the source term; it is important to harmonize time resolution characteristics of a source term and meteorological data in use; For example, user in VALMA can separately select from ready-made source term files, grid specification files, etc. if not defining everything anew.
 - d. Institutions should resort to reliable meteorological data provider(s) and implement special algorithms to deal with numerical weather predictions and meteorological data from meteorological tower(s) around facilities in case of emergency, taking into account type of calculation, code requirements, data resolution and format (basically, for the far-range modeling numerical weather prediction data is practically the only way to input meteorological data). Data downloading to the dispersion analysis tool or computer should be automated in this case;
 - e. Code users should take part in emergency exercises, special code users group meetings, etc. on a regular basis to improve their professional skills and support their qualifications. Benchmarking activities, especially with experts from adjacent Institutions/countries, will benefit the emergency preparedness capabilities, too;
 - f. Code users should be in touch with developers' team to receive qualified help on code features. User-guide information should be known to a model user before running the model and before presenting the results. In the worst case, if a user gets unphysical results, he/she should explore the causes and re-do the calculations. In turn, unphysical results cannot be presented to decision makers as this will misguide their decisions;
 - g. For the JRODOS users, it is important to identify the relation between the magnitude of release and the expected scale of radiological consequences to set up a computational grid in calculations based on Local Scale Model Chain (LSMC). This can help to avoid the issues related to averaging in cell. Preparation of the receptors around a facility to use the option "interpolate to the point" would be justified in those cases;
 - h. It is reasonable to rank optional atmospheric dispersion models integrated into JRODOS system according to the cases of their application (e.g., while source term uncertainties are high, a faster model such as RIMPUFF can be used);
 - i. When OILs options are implemented in a dose projection tool, it is important to pay attention to and verify the relations between OILs and generic criteria results calculated (e.g., dose rate against 7-day equivalent and effective doses);
 - j. The scope and structure of the results report should be adopted regarding requirements of following data consumer (e.g. decision maker, other institution

- 533 or emergency of other countries); it is preferable to use an automated report
534 generation option with prepared geographical or other auxiliary information;
- 535 k. The use of the matched-pairs analysis was found very useful to test the validity
536 of the tools and of the methodologies set-up to use them, comparing the results
537 against validated parameters well-established in the literature; this can be a
538 viable option to verify the quality of the results when experimental data are not
539 available;
- 540 l. The values used to perform the code-to-code intercomparison showed non-
541 negligible differences in some radiological quantities of importance for
542 emergency preparedness and response. This suggests that future activities in
543 the field of code use validation should be supported and realized in order to
544 obtain better harmonization of results between TSOs in Europe;
- 545 m. The teams involved in BARCO consider this type of benchmarking activities of
546 special relevance in assuring the maintenance, dissemination and
547 strengthening of the operational knowledge and experience necessary to
548 perform response assessments, therefore they think that such activities should
549 be carried out more regularly and extensively, also within more structured
550 frameworks at EU level.

551 **6 CONCLUSIONS**

552 The expertise in the assessment and forecasting of radiological consequences may
553 vary slightly from country to country with regard to the methodological approaches, the use
554 of models of atmospheric dispersion and dose projection, databases, calculation
555 procedures, etc. Possible differences in the assessments conducted by experts in different
556 countries and institutions can take place due to a number of different factors: from the use
557 of different sources of information and skills of assessor to the specificities of national
558 requirements. These factors need to be identified both in practice and theoretically. Hence,
559 looking at the novel trends, actual international programs and projects such as IAEA's CRP
560 J15002 [29], OECD NEA FASTRUN [7], US NRC's RAMP [6], emergency preparedness
561 and response modeling resources should be focused on the harmonization of existing
562 approaches with radiological consequences assessments.

563 The BARCO project demonstrates the good practice of comparison on the set of
564 quantities, the frame, scope and format of benchmarking procedure, allowing for a
565 successful use of initial data in each decision support system or code and providing a good
566 understanding of the results behavior under the set of dose projection tools. In particular,
567 some features of the result quantity fields may be explained by the type of dispersion
568 modelling: Gaussian, Lagrangian or Eulerian.

569 Code-to-code analysis and matched pairs analysis were selected to obtain the general
570 picture of data deviations between participants' simulations, and to highlight potential ranges
571 of deviation among the results. The MPA may be used even for analyzing single code
572 results. The method can play a significant role in the selection of benchmarking quantities
573 for further comparison activities.

574 As an endpoint of BARCO results processing, a set of recommendations was provided
575 to achieve a common view on the use of dose projection tools, reducing the number of
576 deviation factors that affect decision making, avoiding mechanical errors, non-physical
577 calculation outputs or their failing interpretation. These kinds of activities between
578 neighboring countries might be applied as an effective instrument of dose projection tools
579 usage harmonization as recommended by the HERCA-WENRA Approach [28].

580 The era of new designs such as small modular reactors calls for actual challenges, e.g.
581 establishing the size of emergency planning zones [30] in near range and complex terrain.
582 Regarding such task, conducting the same kind of benchmark can be applied as well.

583

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587 *calculations.*

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