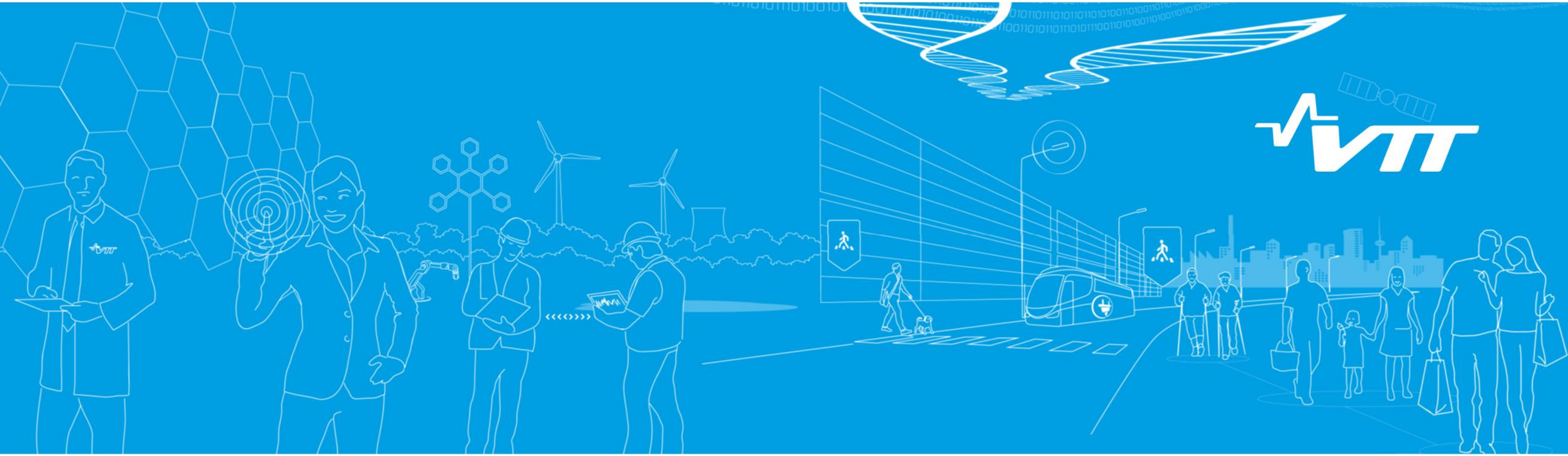


VTT Nuclear Safety (Finland)
- Dispersion and Dose Assessment

IMUG Meeting, 10 June 2019, NRC

Mikko Ilvonen & Jukka Rossi, VTT

Main contents of presentation

1. Nuclear power in Finland
2. Nuclear fission research at VTT Nuclear Safety
3. ARANO short-range level 3 PSA code by VTT
4. VALMA long-range code by VTT
5. Dose probability distributions up to 300 km
6. Ingestion pathways for Nordic agriculture
7. EPZ right-sizing methodology
8. Code comparisons ARANO-VALMA-MACCS

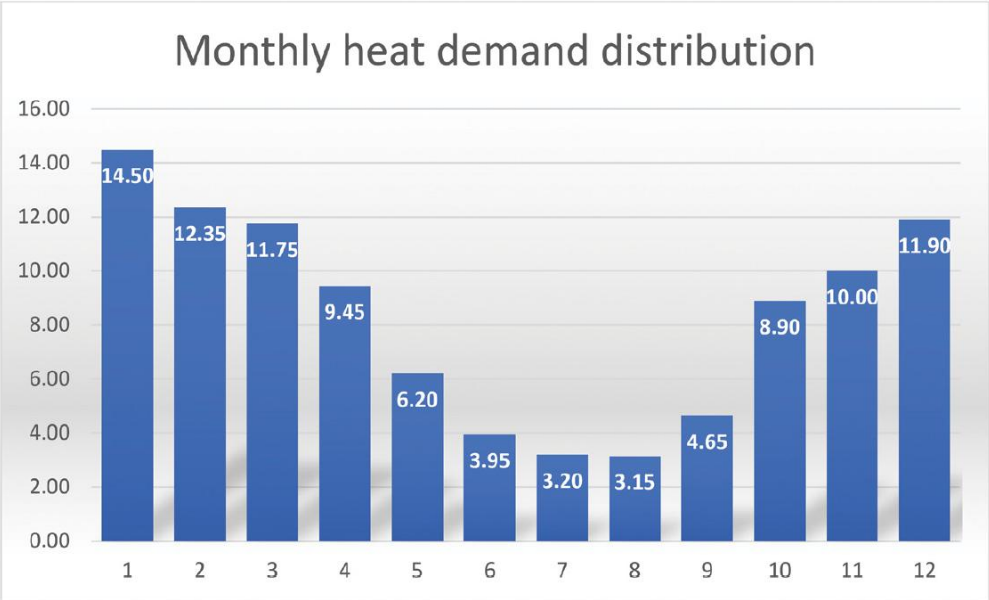
Nuclear power in Finland (Regulator: STUK)

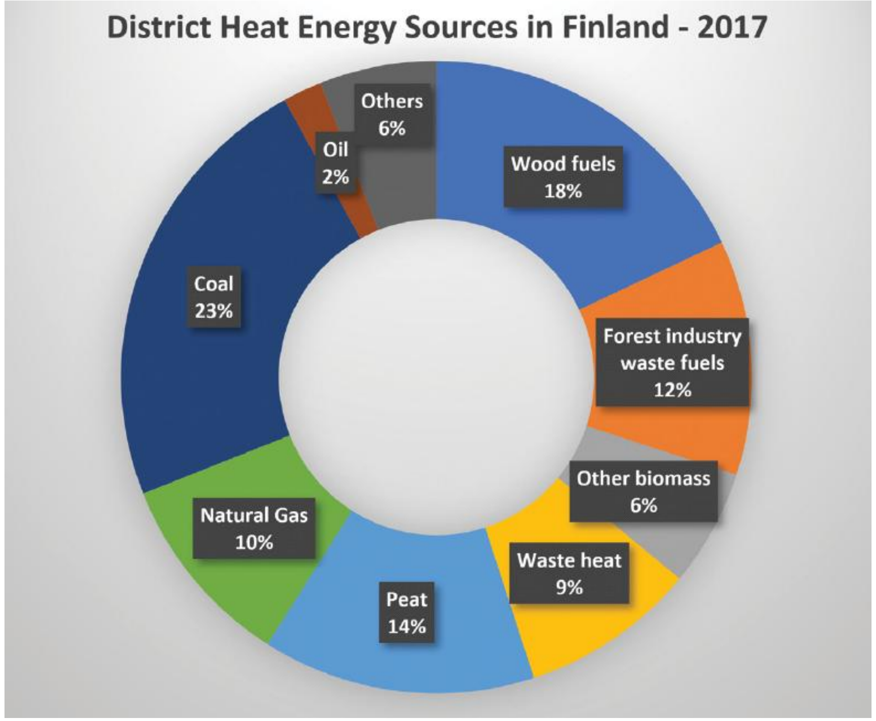
- Loviisa (owned by Fortum)
  - 2 x Soviet VVER-440
- Olkiluoto (TVO)
  - 2 x Swedish BWR
  - French EPR expected online 2019
    - Many delays, e.g. piping vibration (2018)
    - Got operating license in early 2019
- Hanhikivi (Fennovoima)
  - Russian VVER-1200 planned
    - Application for construction permit (2015)
    - Still to be completed by Fennovoima
    - STUK assessment in 2019?
- VTT (green) in Espoo, near Helsinki

Map from Wikipedia

Nuclear power plants in Finland (**view**)
Active plants
Planned plants

Future: Nuclear district heating in Finland?





- (Source of graphics: Partanen 2019, Nuclear DH in Finland)
- Several cities have expressed their interest in nuclear DH
- In February 2019, the Finnish Parliament voted 170-14:
- To pass the law for banning coal in energy use by 1st May 2029.
- Schedule too tight for SMR heat?

Coming update of Nuclear Energy Act & Decree; Potential for more SMR-tailored licensing? (1)

- Source: J Louvanto, MEAE (Finnish Ministry of Economic Affairs and Employment) & M Tuomainen (STUK)
- Going to be a big, long-lasting process (complete: 2024 ?)
- Considered in a group involving ministry, STUK (regulator), universities and energy industry
- SMRs kept high on the agenda
- Topics: Site approval, type approval, waste management, security
- Current licensing was made considering large LWR (but some exceptions for small research reactors)
- Political decision on SMR needed: overall good of society?
- STUK resources for SMR activities are very limited
- Same level of safety (consequences) is expected and must be demonstrated

Areas in VTT nuclear fission research

- **Plant safety and performance**
  - Deterministic safety & engineering analyses
    - Fuel and reactor physics
    - Thermal hydraulics & integrated analyses
    - Accident and transient analyses
    - Severe accident management
    - Radiological release analysis
    - Fire and evacuation safety analysis
  - Probabilistic safety analysis (PSA)
  - Structural safety and integrity of reactor circuit and structures
  - Material performance assessment
  - Systems engineering
  - Automation (I&C) validation and verification
  - Human factors engineering, control room
  - Organization, safety culture
  - Remote handling

TVO, Olkiluoto NPP site

VTT Triga Mark II RR 1962-

- **Waste management and geological disposal**
  - Performance analyses of technical and natural barriers of repositories
  - Technology development of engineered safety barriers

- **New generation reactors and fuel cycle**

VTT-developed dose assessment models

- **ARANO:** (PSA3 code): used in siting studies in 1975-76, applicable at short ranges from source (10-20 km, in some cases max 100 km)
- **ROSA:** used at Finnish NPPs since 1991, based on ARANO, weather data at 10 min intervals; calculation up to 20 km radius; still used at Olkiluoto?
- **TRADOS:** 1983; ’emergency version’ for Unix in 1992; long-range dispersion model (thousands of km); dispersion by FMI, doses by VTT
- **SILAM:** VTT participation in development in the 1990s
- **VALMA:** (first demonstration in 1998); user interface in Windows
  - Dispersion based on weather mast data or (preferably) SILAM
- **DETRA:** biospheric transport (deposition > foodstuff > humans) of radionuclides & related dose assessment

ARANO short description

- **ARANO** (Assessment of radiological consequences of atmospheric radioactive releases), developed at VTT in the 1970's
- Dispersion: 'Traditional' straight-line Gaussian, augmented with Kz vertical
- Initially used for nuclear power plant siting studies.
- Has been used to estimate effectiveness of different countermeasures.
- Has been used by VTT to support STUK in various safety assessments for constructing new power plant, dismantling a research reactor, and for disposal site
- Functionality comparable to MACCS, but less choices available:
  - Atmospheric transport and deposition onto the ground
  - In addition to a single dispersion case statistical effect of variability in weather
  - Dose pathways: cloudshine, groundshine, inhalation, ingestion, deposition onto skin
  - Protective actions during emergency, intermediate, and long-term phases
  -
  - Offsite consequences:
    - Doses to individual and population, health effects
    - Economic costs, land contamination

Pasquill model (general)

$$\chi(x,y,z,t) = q_0(t - x/u_H)\frac{1}{2\pi\sigma_y\sigma_z u_H}\exp(-\frac{y^2}{2\sigma_y^2})\cdot$$
$$(\exp(-\frac{(z-H)^2}{2\sigma_z^2}) + (\exp(-\frac{(z+H)^2}{2\sigma_z^2}))$$

K_z model for vertical dispersion (ARANO)

$$(\frac{\partial C_z(z,t)}{\partial t})_m = \frac{\partial}{\partial z}[\ K_z(z)\frac{\partial C_z(z,t)}{\partial z} - v_d C_{zm}(z,t)\ ]$$

Effect of wet deposition on the plume

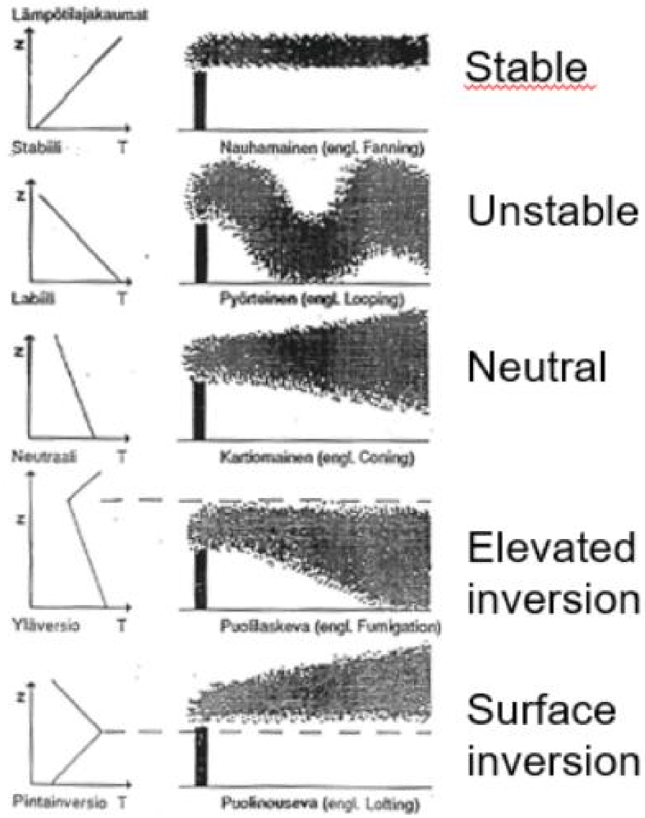
$Q/Q_0 = e^{(-\Lambda \cdot x/u)}$

Λ is washout coefficient (7E-5…5E-3 s^{-1})

- K_z (z) = coefficient of turbulent transfer
- V_d = dry deposition velocity (zero for gases)

ARANO cloudshine dose assessment

- Not using the uniform semi-infinite cloud approximation
- Near the release source, the size & shape of the plume may differ substantially from that approximation
- Cloudshine from actual shape of the plume
  - Algorithm is based on pre-calculated dose rate files for successive stages of the evolving Kz vertical profile
  - Wind meandering in longer duration releases accounted for



ARANO: SOURCE TERM

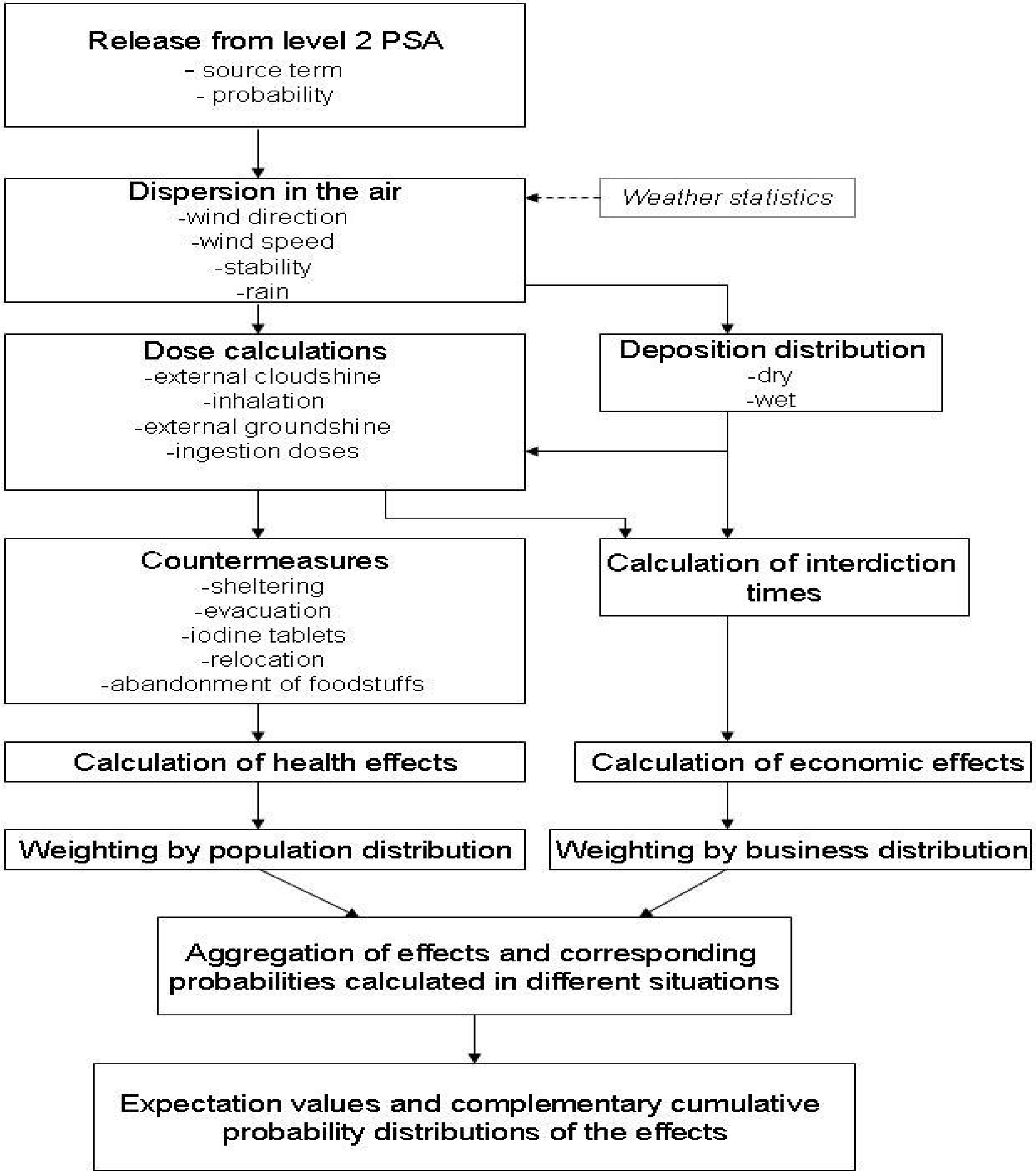
1. Define the release of the isotopes in Bq or
2. Give the reactor inventory in Bq and the release fraction for each element group.

Element group	Nuclides
1. Noble gases	Kr, Xe
2. Halogens	I, Br
3. Alkali Metals	Cs, Rb
4. Chalcogens	Te, Sb
6. Platinoids	Ru, Rh, Pd, Mo, Tc, Co
7. Lantanides	La, Zr, Nd, Nb, Pm, Pu, Pr, Y, Cm, Am
8. Others	H, N, C, Ar, Cr, Mn, Fe, Zn, Ag

Inorganic / organic iodine compounds

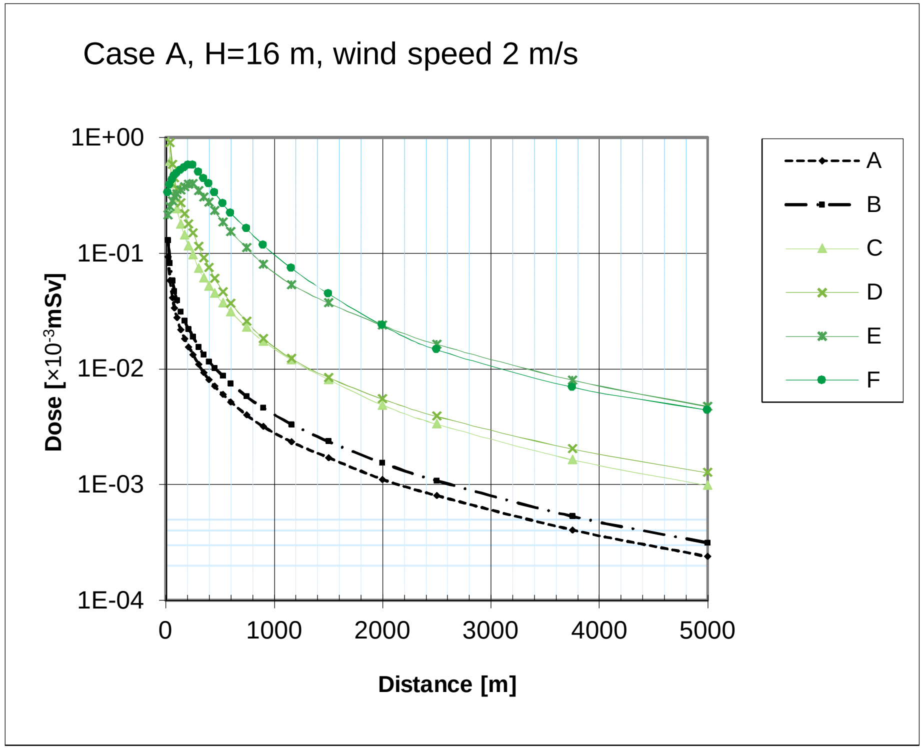
DEFINE
- start and end time of the release (relative to shutdown)
- warning time (time interval between the predicted release and the real release)
- effective release altitude (plume rise separately)

The flow chart of the ARANO computer code



Samples of ARANO results

Sample Fir1 release (VTT research reactor) Triga Mark II

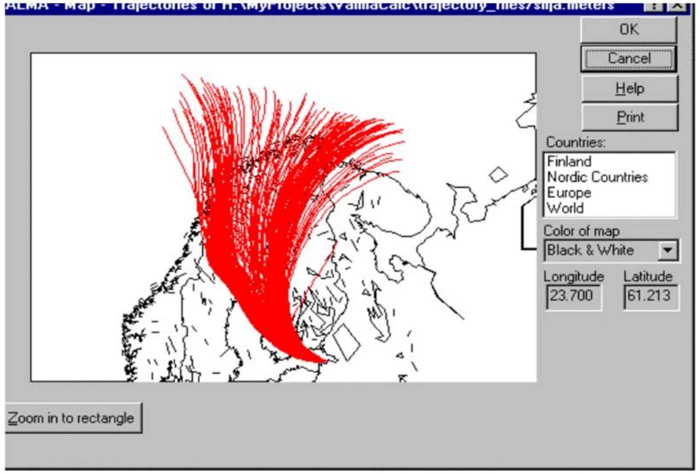


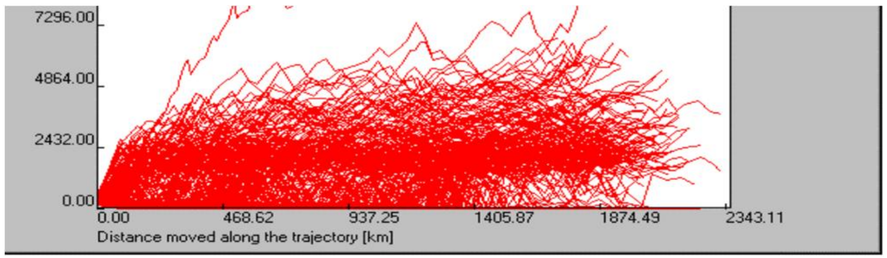
Dose in the Pasquill dispersion conditions.

- ARANO works fine for near field
- Stable conditions E, F have maxima at appr. 200 m

- Note: Scaling by power would practically appr. multiply the doses by a constant factor

Map View and Side View of Sosnovyy Bor SILAM particle trajectories in VALMA



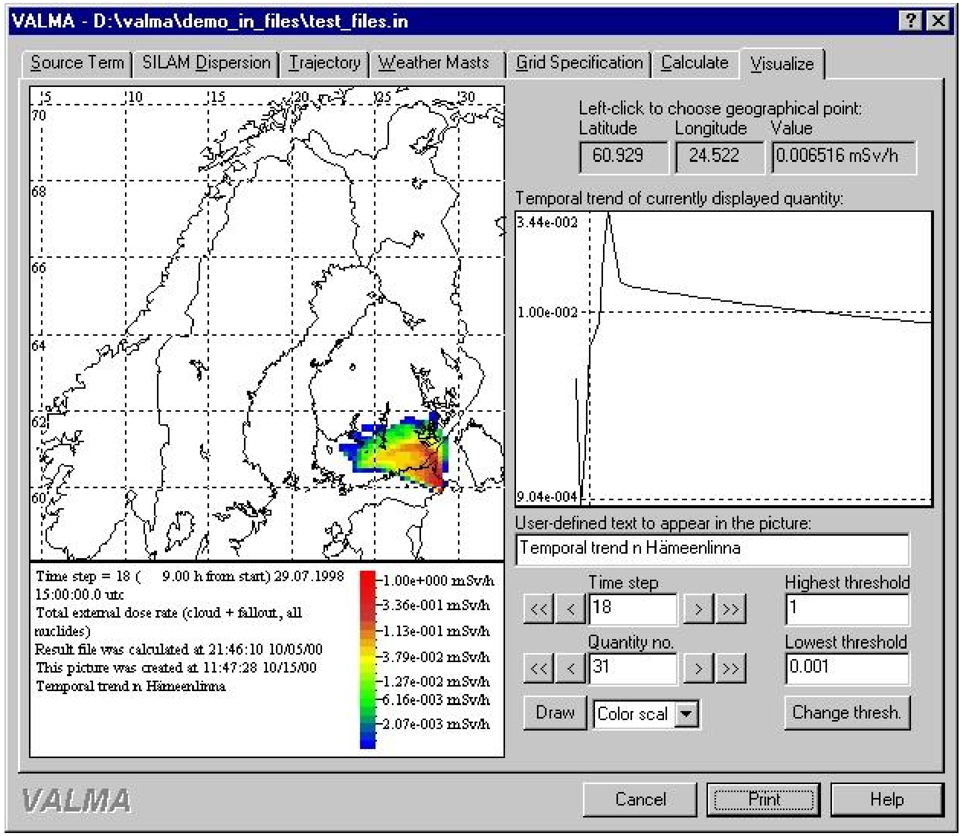


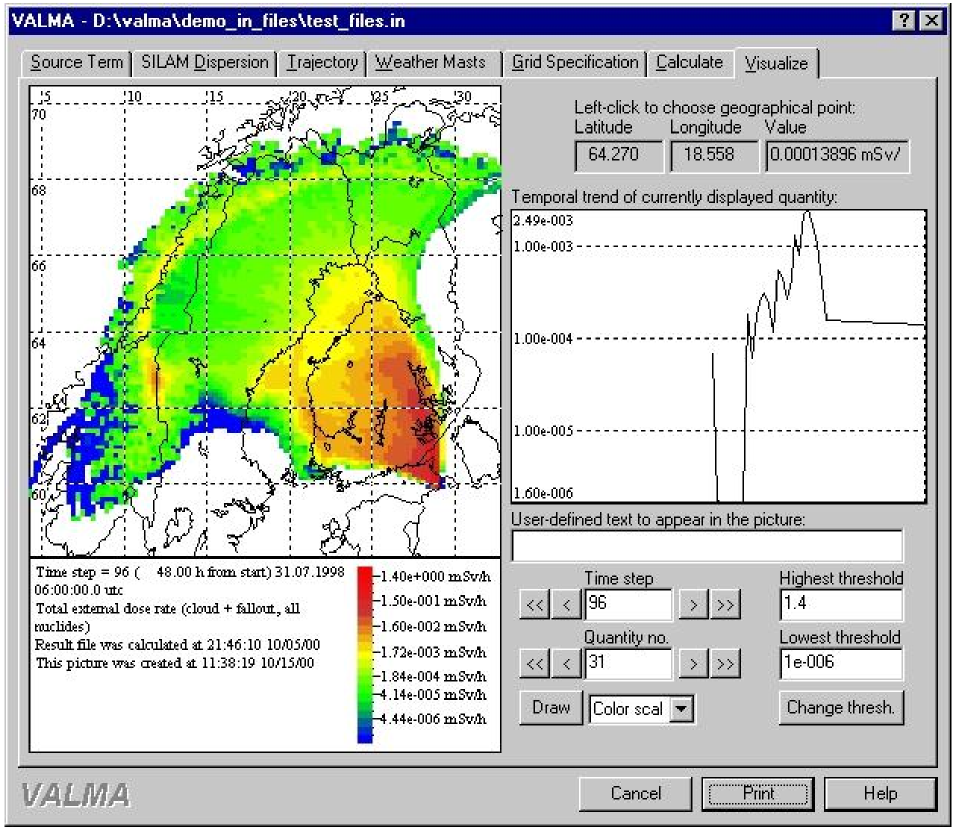
VALMA comes with higher-fidelity Dispersion, but takes more CPU:

- Connection to 3D numerical weather prediction (NWP)
- Option to use one-point mast-based weather data
- Release divided temporally and spatially to n parts (‘puffs’)
- Best suitable for distances > 5 km
- Made originally for emergency preparedness & response

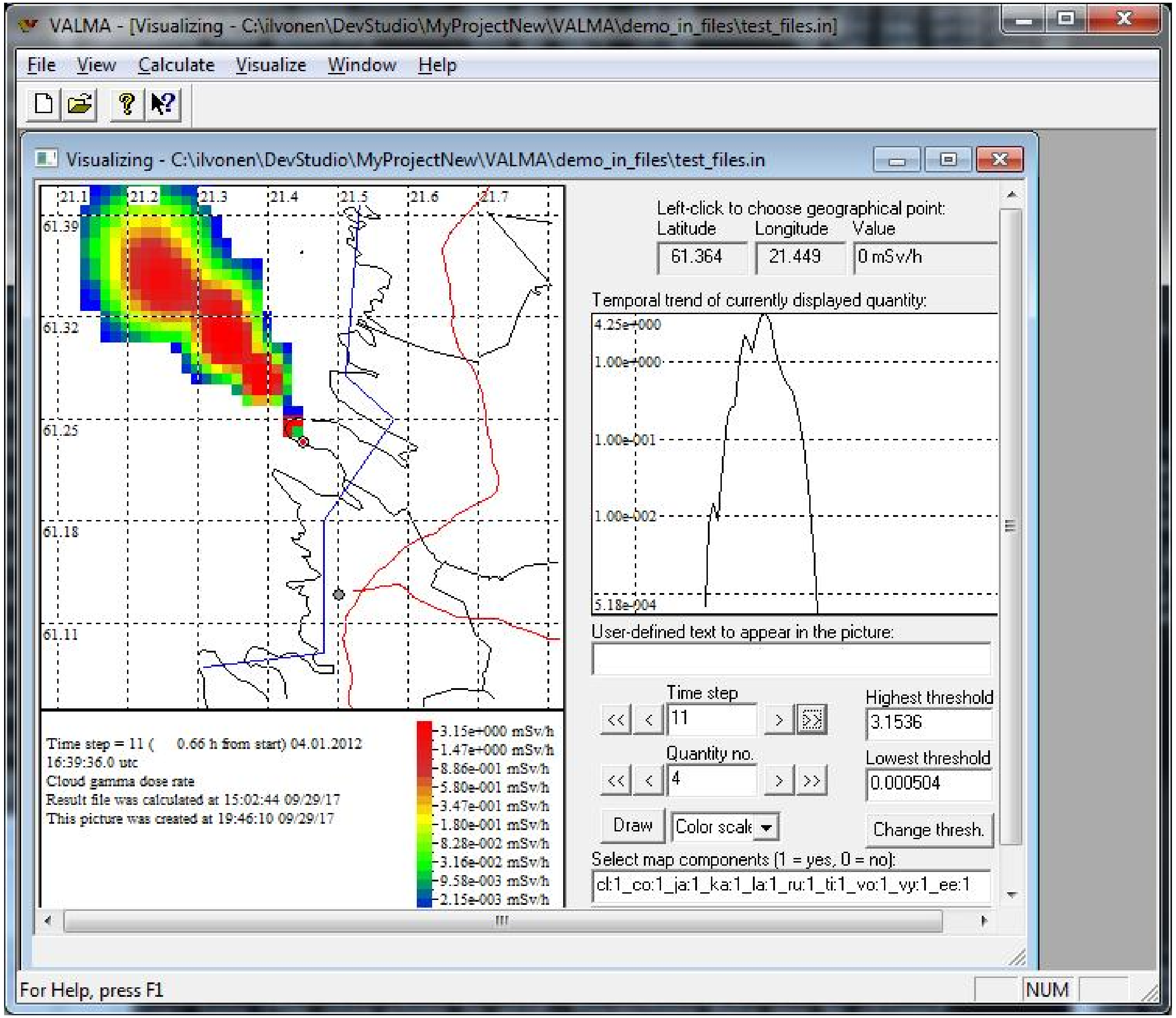
Example: Sosnovyy Bor, Russia

- Total external dose rate mSv/h (cloud and fallout) at 9 h and 48 h after start of release, source is a hypothetical release at Sosnovyy Bor



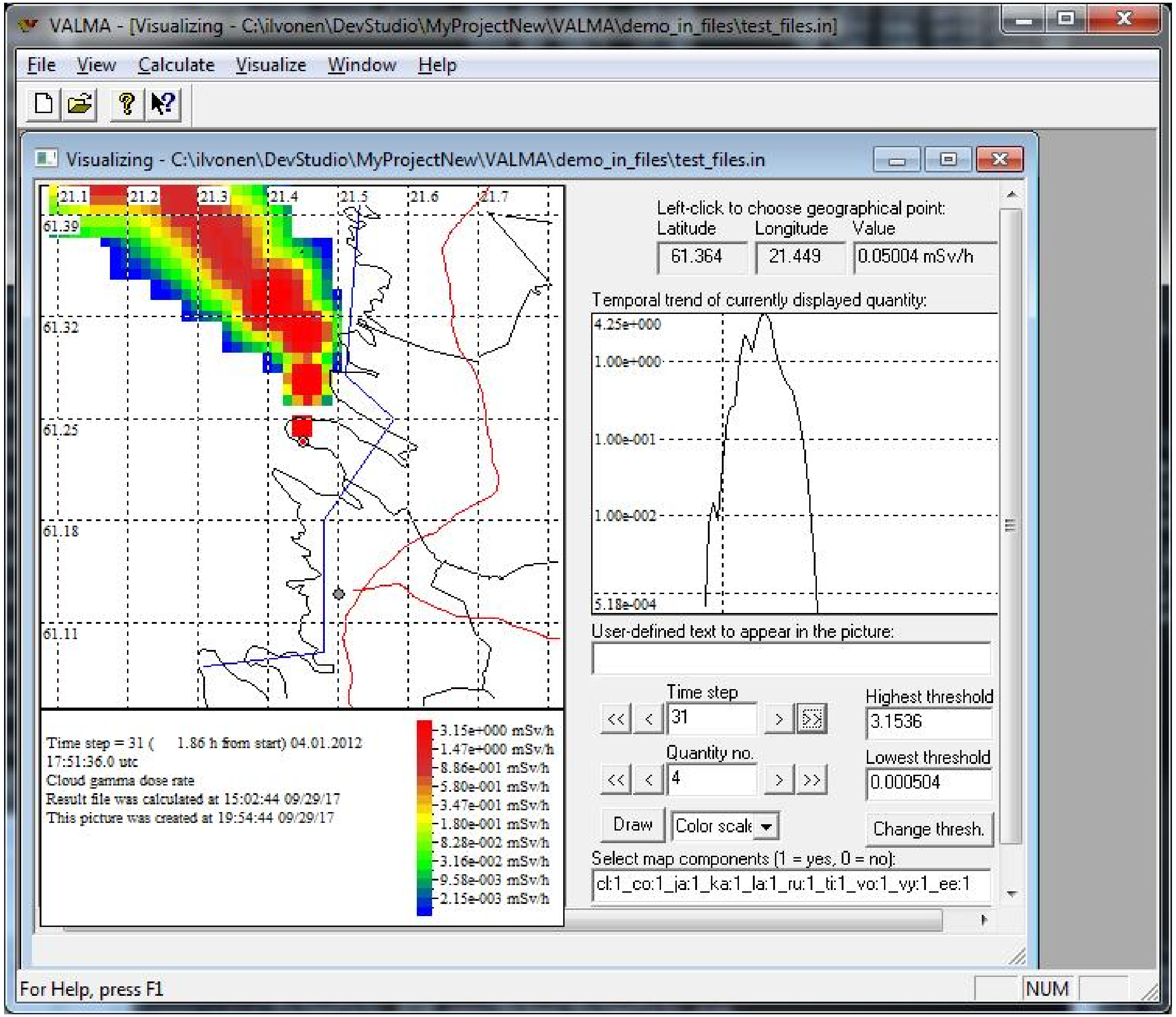


Bigger release VALMA results, 1/4, (cloudshine dose rate, 40 min from start)



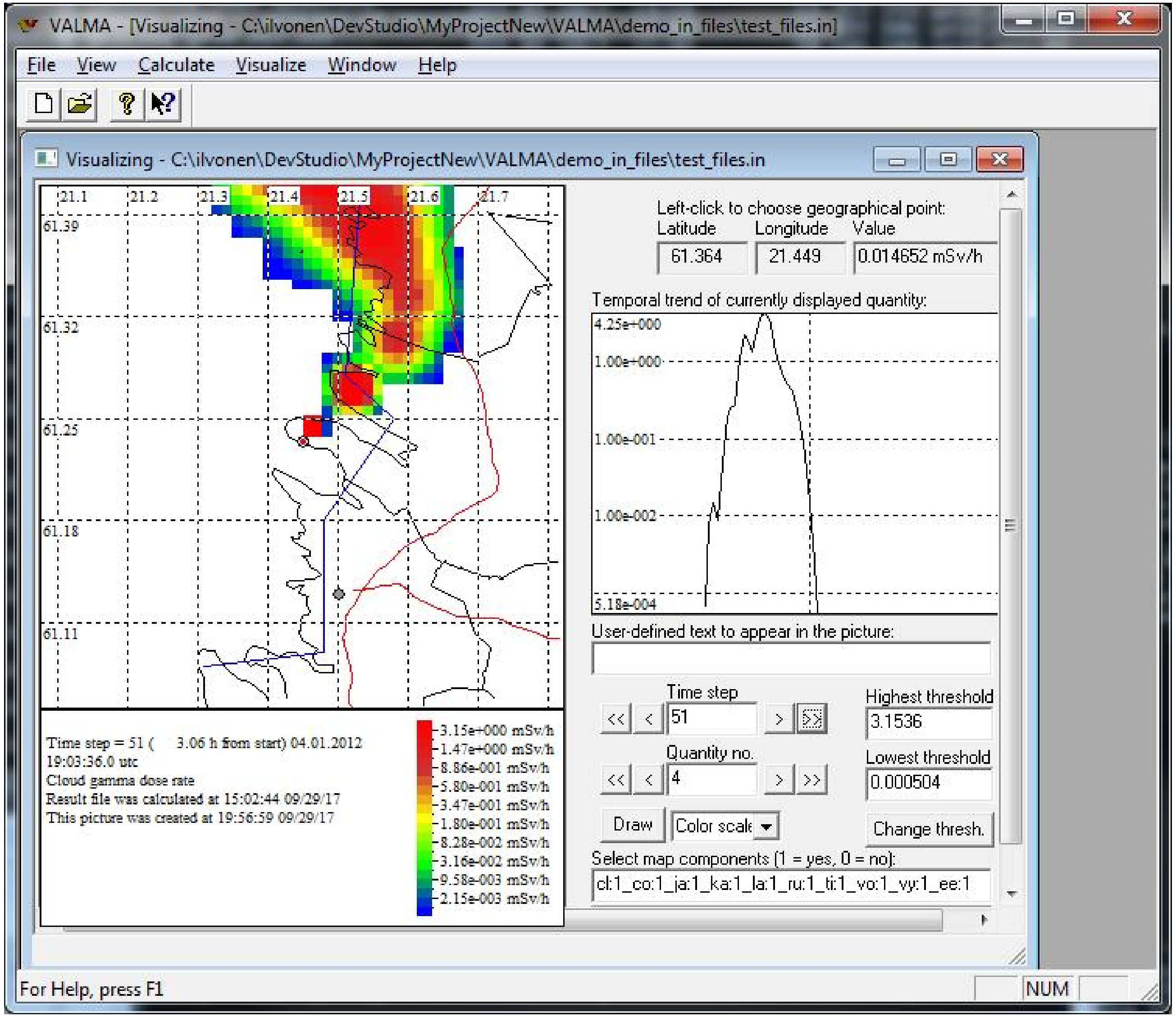
- One colored square is appr. 800 m x 800 m
- Map area is appr. 40 km x 40 km
- Olkiluoto in the middle
- City of Rauma marked with grey
- Wind speed seems appr. 8 m/s

Bigger release VALMA results, 2/4, (cloudshine dose rate, 1 h 52 min from start)



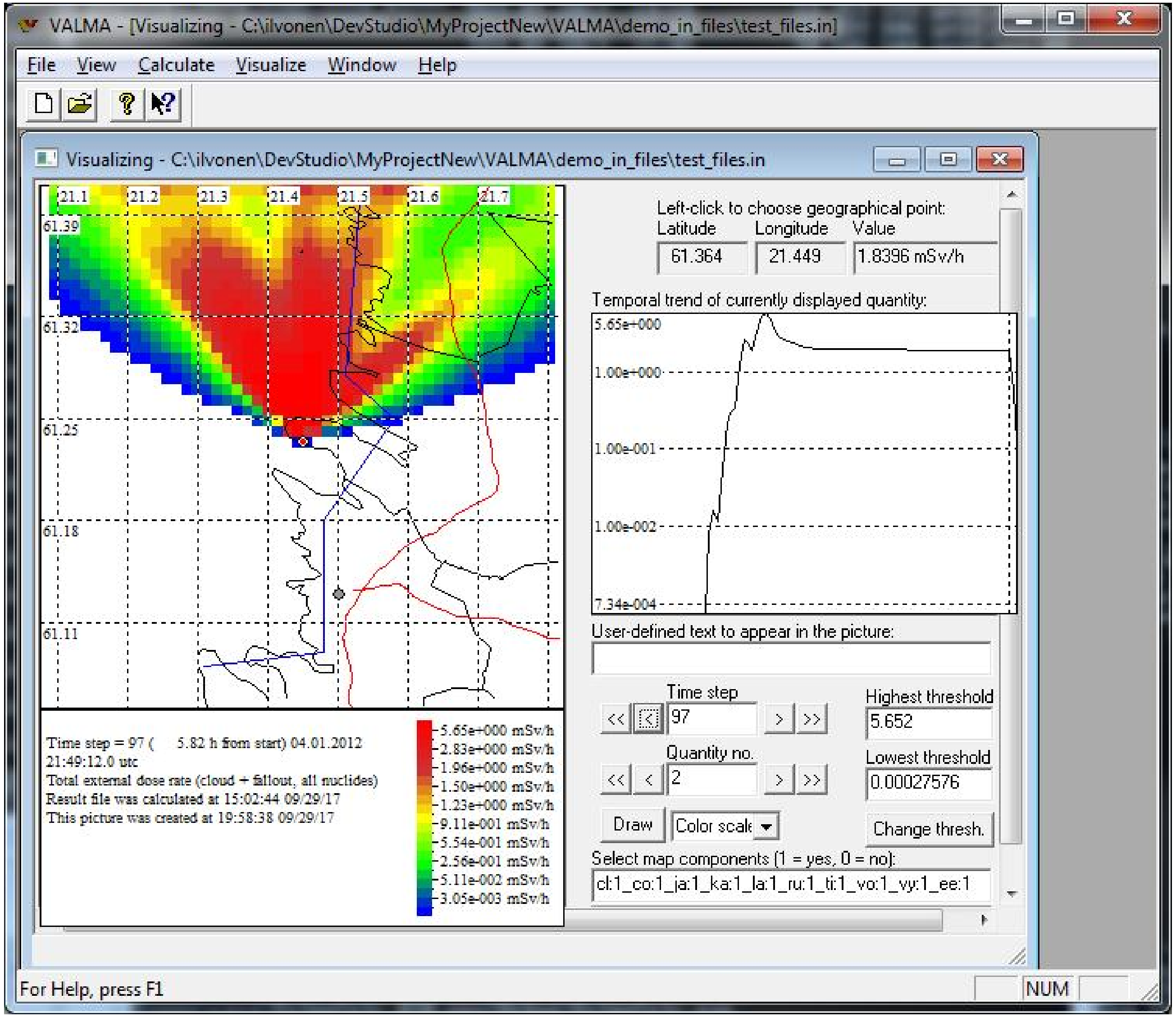
- One colored square is appr. 800 m x 800 m
- Map area is appr. 40 km x 40 km
- Olkiluoto in the middle
- City of Rauma marked with grey

Bigger release VALMA results, 3/4, (cloudshine dose rate, 3 h 4 min from start)



- One colored square is appr. 800 m x 800 m
- Map area is appr. 40 km x 40 km
- Olkiluoto in the middle
- City of Rauma marked with grey

Bigger release VALMA results (cloudshine+groundshine dose rate, 5 h 49 min)



- One colored square is appr. 800 m x 800 m
- Map area is appr. 40 km x 40 km
- Olkiluoto in the middle
- City of Rauma marked with grey

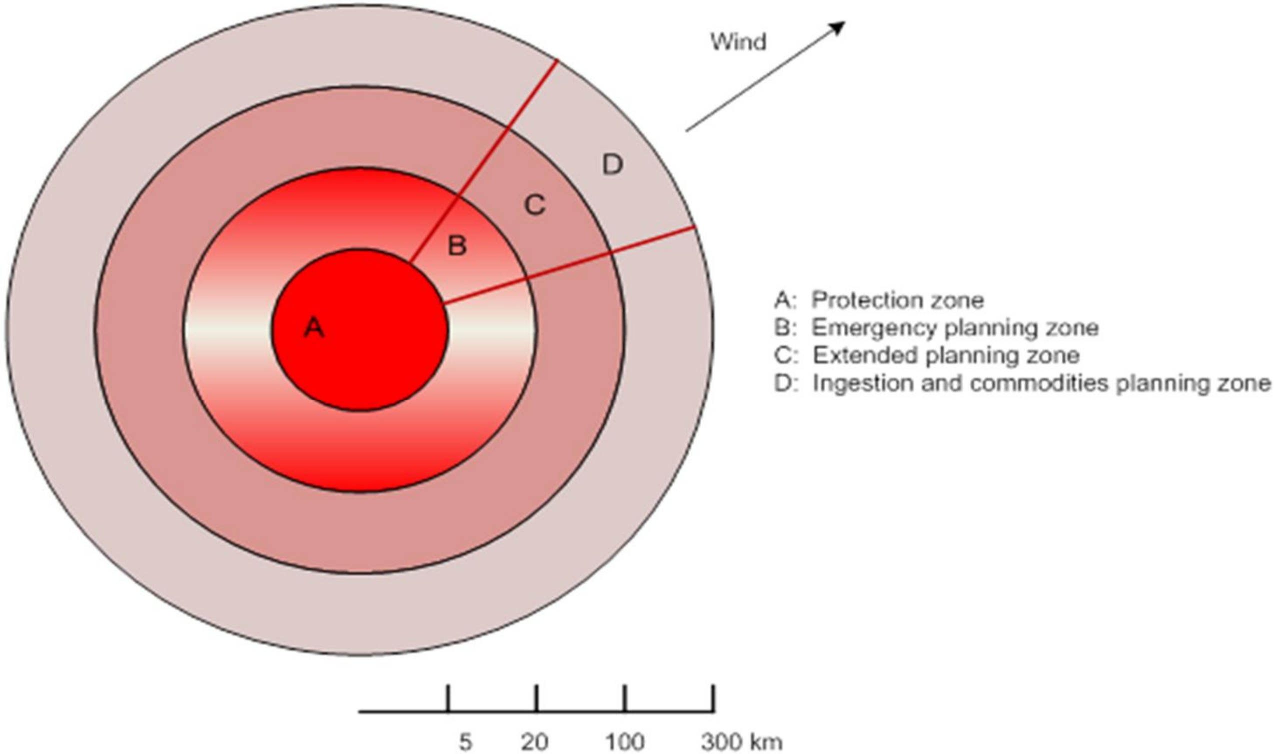
Recent years' work in SAFIR research program

- 01377-13: Fukushima dispersion and doses with ROSA and VALMA
- 00432-15: Dose probability distributions up to 300 km (EPD, ICPD)
- 00589-16: VALMA-calculated probability distributions with 1 a SILAM data
- 00695-17: Assessment of ingestion doses with VALMA
- 00651-18: Off-site radiological consequences from an SMR unit
- 00885-18: Estimates of health effects with VALMA
- 06998-18: EPZ of SMRs by plant suppliers vs. regulatory bodies
- 00136-19: Code-to-code comparisons of ARANO, VALMA and MACCS

- Work going on in 2018-2020:
  - IAEA CRP I31029: Methodology for EPZ assessment of SMRs

- (The codes refer to VTT publications, e.g. VTT-R-01377-13)

Zones A & B are used in present planning; C & D are based on new IAEA recommendations



- A: Precautionary action zone PAZ, 5 km
- B: urgent protective actions planning zone UPZ, 20 km
- C: Extended planning zone (EPZ), 100 km
- D: Ingestion and commodities planning zone (ICPZ), 300 km

Emergency preparedness zones around a nuclear power plant (not in scale)

What countermeasures may be relevant outside 20 km ?

- New IAEA and WENRA recommendations call for preparedness for radiological emergency even up to 300 km distance

SILAM dispersion data for 2012 (FMI), used in VALMA dose calculations

- Calculated by Julius Vira (FMI), October 2015
- 1 Jan … 31 Dec 2012
- For Olkiluoto NPP site
- Air parcel trajectories (i.e. massless particles)
- No gravitational settling, even for aerosol form particles
- ECMWF (European Centre for Medium-range Weather Forecasts) numerical weather prediction model
- Horizontal resolution of NWP data was 16 km x 16 km
- 20 trajectories every 12 min (= 100 / hour), appr. 9 GB
- A total of 878400 trajectories, followed for max. 96 h each
- Release height 0…200 m
- In VALMA, it was specified: 4 h cooling time, 3 h release duration

Considered locations around Olkiluoto 3

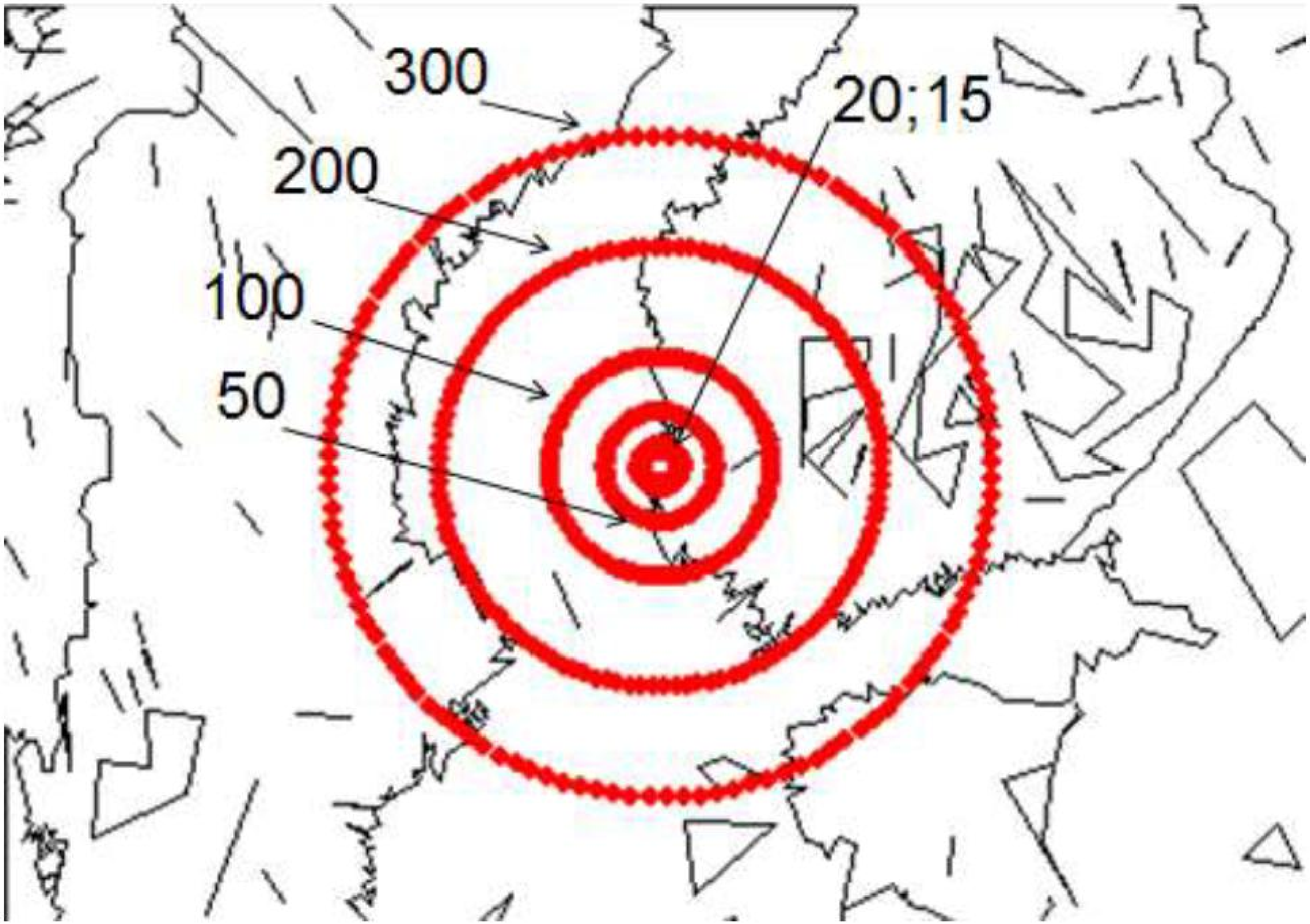


Figure 3.1. Graph of the calculation distances around the nuclear power plant. Ring 1 corresponds to 15 km,ring 2 to 20 km, ring 3 to 50 km, etc.

Picture from VALMA GUI

Total dose cloudshine + groundshine + inhalation [mSv] at the 6 distances, 95% percentile, case 3. Time integral of 1 year.

Distance [km]	**VALMA, Mean**	**VALMA, Median**	**VALMA, Maximum**	**ARANO (mean)**
15	4550	4770	9770	3000
20	3180	3300	6850	2000
50	965	969	2130	550
100	439	400	1020	150
200	180	150	435	40
300	118	94.3	287	20

AGRID model description 1/2

- VTT-made nutrition dose code, ’Agricultural Doses’
- Originally inspired by FOOD-MARC model of the British NRPB
- 3 vegetable dose pathways (green vegetables, grain, roots)
- 2 animal dose pathways (cow milk, cow meat)
  - Calculation methods differ for vegetables and animals
- Agrid accounts for Nordic seasons in agriculture
- For the 3 vegetable dose pathways:
  - Dose due to root uptake is present for all time points (of receiving deposition) during the year
    - The next 30 years’ root uptake is taken into account
  - During the growing season (60 d), also direct deposition on plants causes doses to consumers (intake of deposition year)
    - Time delays (rad. decay) before harvesting / consumption

AGRID model description 2/2

§ For the 2 animal dose pathways:

- Pasture – cow – milk – man
  - Effective whole body dose & thyroid dose via milk
- Pasture – cattle – meat – man
  - Effective whole body dose

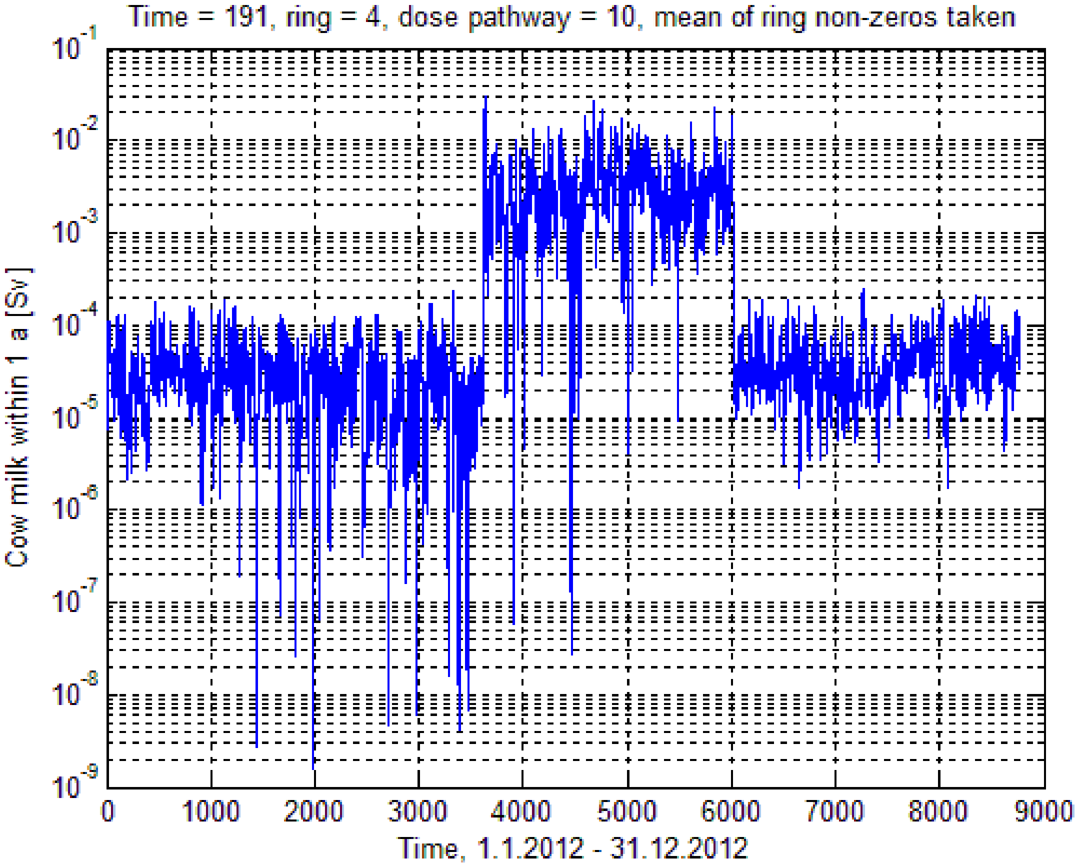
§ Dose is the sum of 3 time periods:

- 1st year, pasture season (100 d) or winter time
- Years 2-3
- Years 4-30, ground assumed to be ploughed after 3 years

Example of dose coefficients table (Ingestion of milk or meat,1 year)

		Summer		Winter	
		Milk	Meat	Milk	Meat
1	KR85	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	KR85M	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	KR87	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	KR88	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	SR89	3.55E-12	7.58E-13	7.15E-14	2.16E-14
6	SR90	2.96E-10	8.65E-11	6.72E-11	2.05E-11
7	SR91	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	Y90	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	Y91	7.37E-14	8.96E-14	1.93E-16	2.00E-14
10	ZR95	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	ZR97	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	NB95	1.26E-11	7.61E-14	1.69E-14	1.66E-15
13	MO99	1.15E-13	5.20E-14	2.02E-27	1.56E-26
14	TC99M	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	RU103	4.00E-16	8.67E-14	1.90E-18	8.08E-15
16	RU105	0.00E+00	0.00E+00	0.00E+00	0.00E+00
17	RU106	1.52E-14	1.20E-11	6.74E-16	2.76E-12
18	RH105	0.00E+00	0.00E+00	0.00E+00	0.00E+00
19	TE129	0.00E+00	0.00E+00	0.00E+00	0.00E+00
20	TE129M	8.00E-13	1.22E-11	3.62E-14	8.89E-13
21	TE131M	0.00E+00	0.00E+00	0.00E+00	0.00E+00
22	TE132	6.35E-14	1.88E-13	2.91E-25	5.86E-24
23	I131	5.08E-11	9.76E-12	2.27E-18	1.46E-18
24	MI131	0.00E+00	0.00E+00	0.00E+00	0.00E+00
25	I132	1.01E-24	2.70E-30	0.00E+00	0.00E+00
26	I133	1.43E-13	1.99E-15	0.00E+00	0.00E+00
27	I134	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	I135	3.19E-17	2.64E-20	0.00E+00	0.00E+00
29	MI135	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Dose from the locally produced milk (consumption of first year), CASA1 source term, mean non-zero value at the distance of 100 km; as a function of release start time.

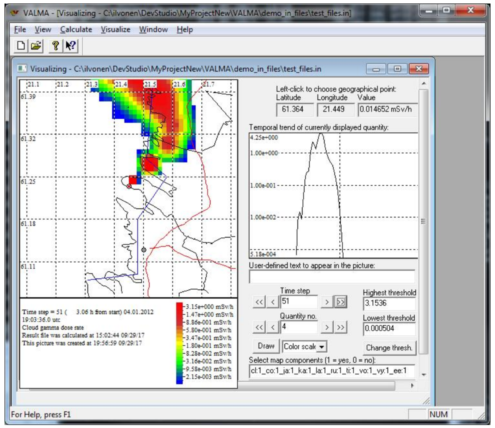


Importance of near-field dispersion effects for SMR (VTT-R-06998-18) >> CFD approach?

- Many SMR designs locate the reactor underground, or at least the size of the building is smaller than for large NPPs. Possibly the initial heat content is smaller. These factors will make the <u>effective release height smaller</u>, meaning a more concentrated radioactive cloud in the nearby areas. Furthermore, the possible offsite adverse effects are inherently located more pronouncedly in the nearby areas only, because of the small source. Potential <u>siting near population centers</u> makes it very important to study those near-field effects in great detail.
-
- <u>Building wake</u>: Turbulent eddies around buildings provide more initial spread.
- <u>Stack-tip downwash</u> (high-rise structures causing downwards transfer of activity concentrations)
- <u>Cloud rise (plume rise)</u>: Initial upward momentum and heat content make the release rise higher than stack height right at the starting point.
- <u>Near-field dispersion parameters: Weather mast measurements</u> may be more reliable near the source than NWP (numerical weather prediction) model, but more masts than one single would make the data even more reliable and complete.
- <u>Very narrow plume</u>: It takes some time for the release to spread in the lateral and vertical directions, and when e.g. using the Gaussian model, choice of appropriate parameters is very important.
- <u>Urban / industrial terrain</u>: Terrain roughness may decrease wind speeds locally and induce turbulence. Furthermore, spread directions may favor street 'canyons' etc.

Code-to-code comparisons of ARANO, VALMA (VTT codes) and MACCS 3.10.2 (NRC)

- ARANO & MACCS:
  - Offsite dose calculations without countermeasures in a single weather condition as well as with the probabilistic approach employing annual weather data.
  - The principal phenomena included in the codes are atmospheric transport and deposition under prevailing meteorology, short- and long-term mitigation actions and exposure pathways, deterministic and stochastic health effects, and economic costs.
- VALMA is more restricted but with higher-fidelity dispersion:
  - Connection to 3D numerical weather prediction (NWP)
  - Best suitable for distances > 5 km
  - Made originally for emergency preparedness & resp.
  - Protective measures not included in the calculations
  - More CPU time



Comparison of ARANO, MACCS and VALMA

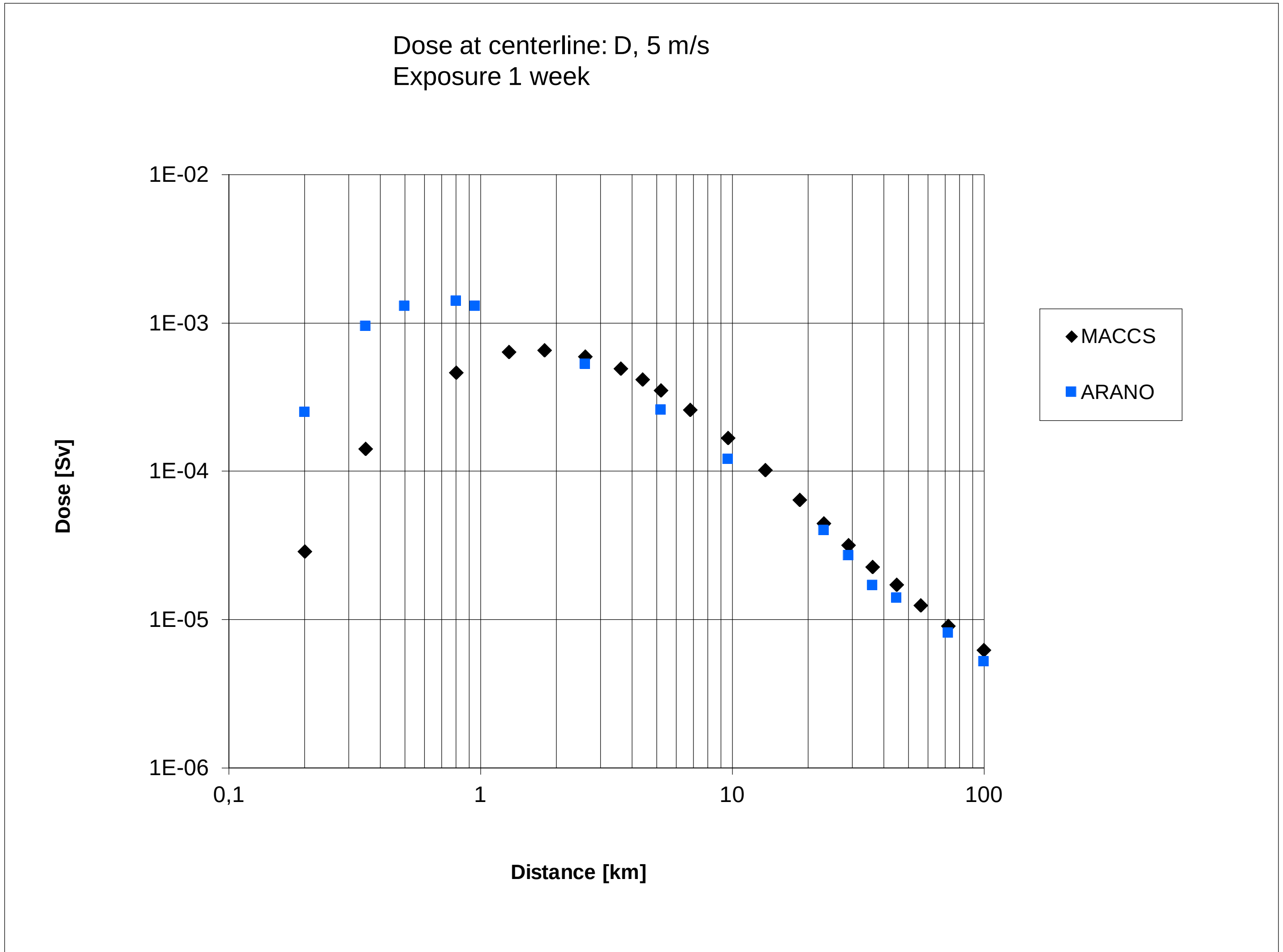
- Note: First ARANO-MACCS comparisons were made in 1982 and 1994
  - OECD/NEA 1994. Probabilistic Accident Consequence Assessment Codes, Second International Comparison, Technical Report EUR 15109, CEC
- VALMA is a VTT-developed in-house code, primarily suited for distances > 5 km, using NWP 3D weather data
- ARANO works well even for near-field (< 500 m)
- Cloudshine from actual shape of the plume
  - Algorithm is based on pre-calculated dose rate files for successive stages of the evolving Kz vertical profile
  - Wind meandering in longer duration releases accounted for

Single weather comparison runs, Non-ingestion exposure pathways

- Cloudshine, groundshine and inhalation. Moreover, resuspension is included in MACCS. Dose is the sum of these components.
- The source term input is: Cs-137 (t_{half} = 30.17 a) 100 TBq, duration of the release 0.5 h, without delay from the shutdown, release altitude 100 m.
- Some weather situations used in single weather cases:

	Stability	Wind (m/s)	Rain (mm/h)	Nuclide (t 1/2)
1, 2	D	5	no rain	Cs-137 (30.17 a)
3	C	5	5	Cs-137
4	F	1	no rain	I-131 (8 d), I-133
5	D	5	0.7	Cs-137

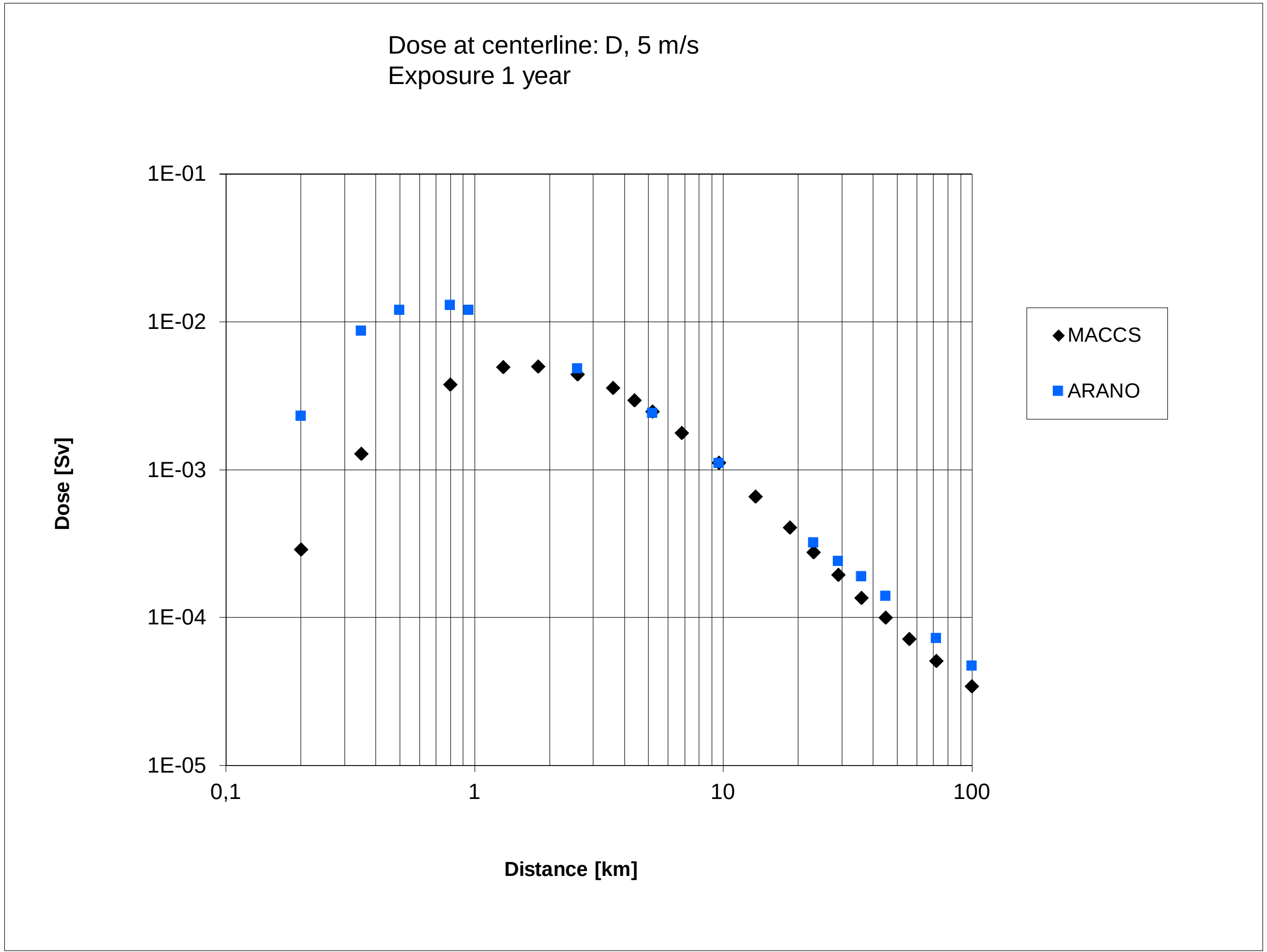
Single weather, Non-ingestion exposure pathways ('1')



- Cs-137, 100 TBq
- Stability D
- 5 m/s
- No rain
- 1 week exp.

- ARANO higher up to 2 km from source
- As much as 10x

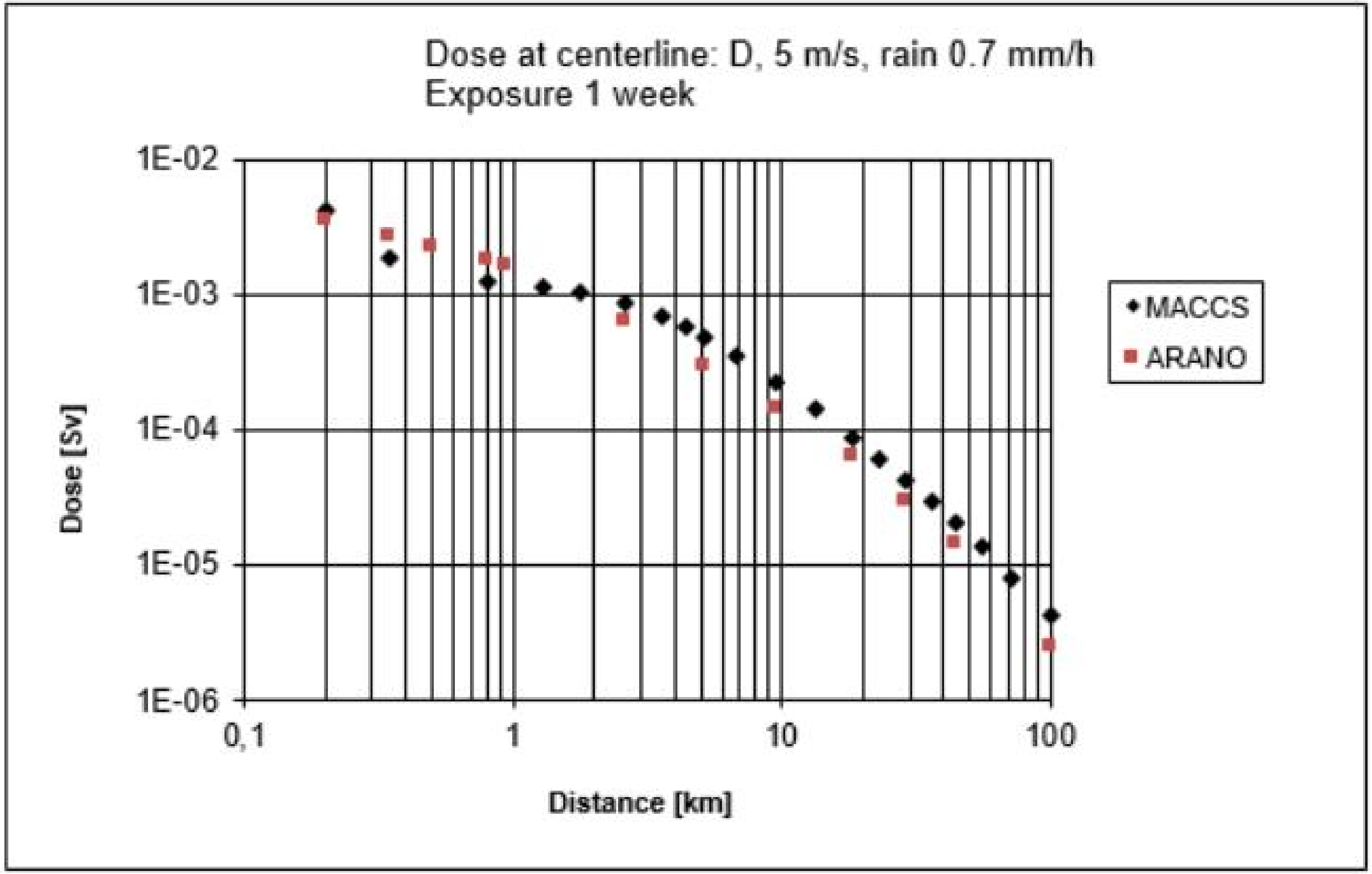
Single weather, Non-ingestion exposure pathways ('2')



- Cs-137, 100 TBq
- Stability D
- 5 m/s
- No rain
- 1 year exp.

- ARANO higher up to 3 km from source (even 10x) and farther than 20 km

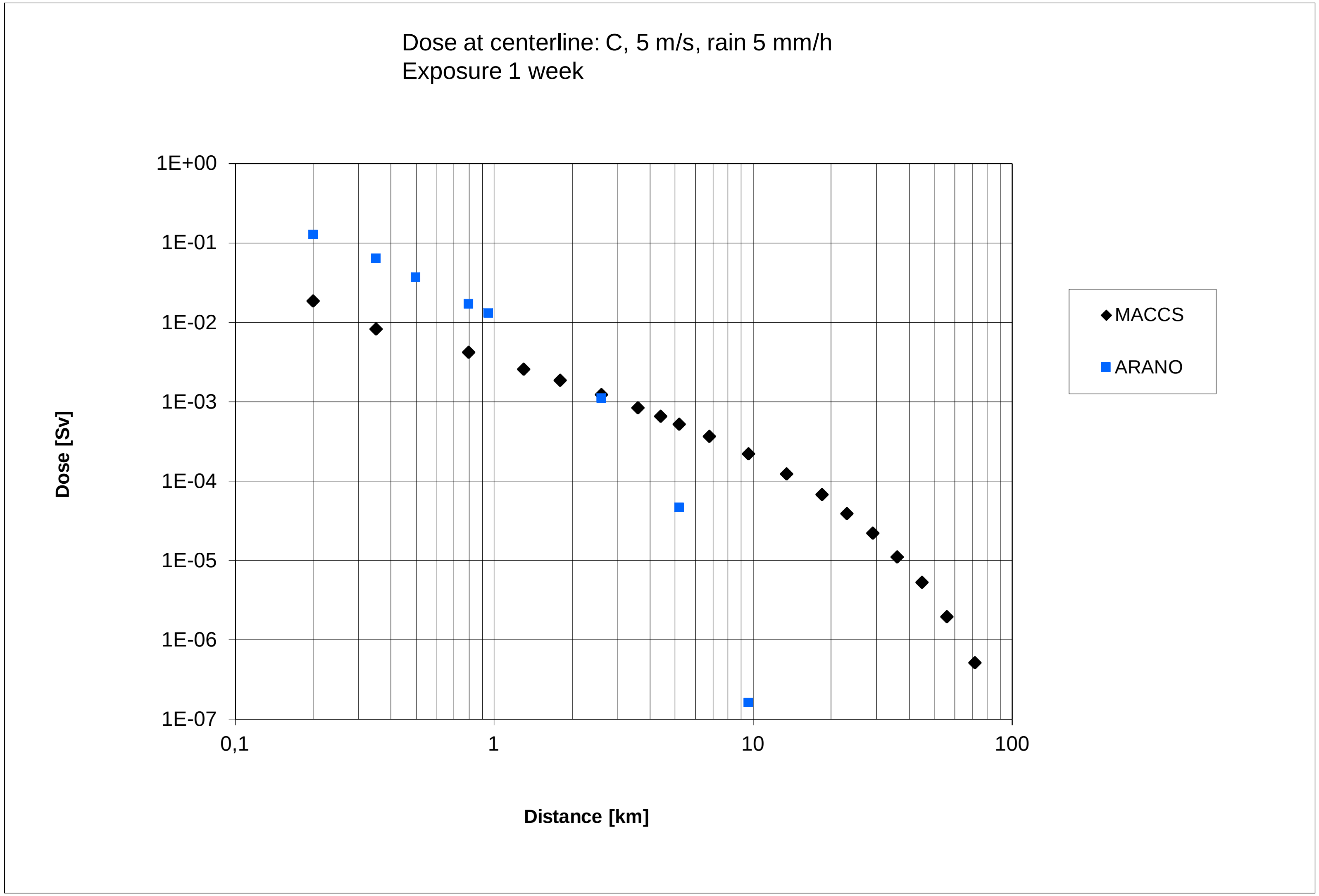
Single weather,
Non-ingestion exposure pathways ('5')



- Cs-137, 100 TBq
- Stability D
- 5 m/s
- Rain 0.7 mm/h
- 1 week exp.

- ARANO higher up to 1 km
- No big difference when weak rain

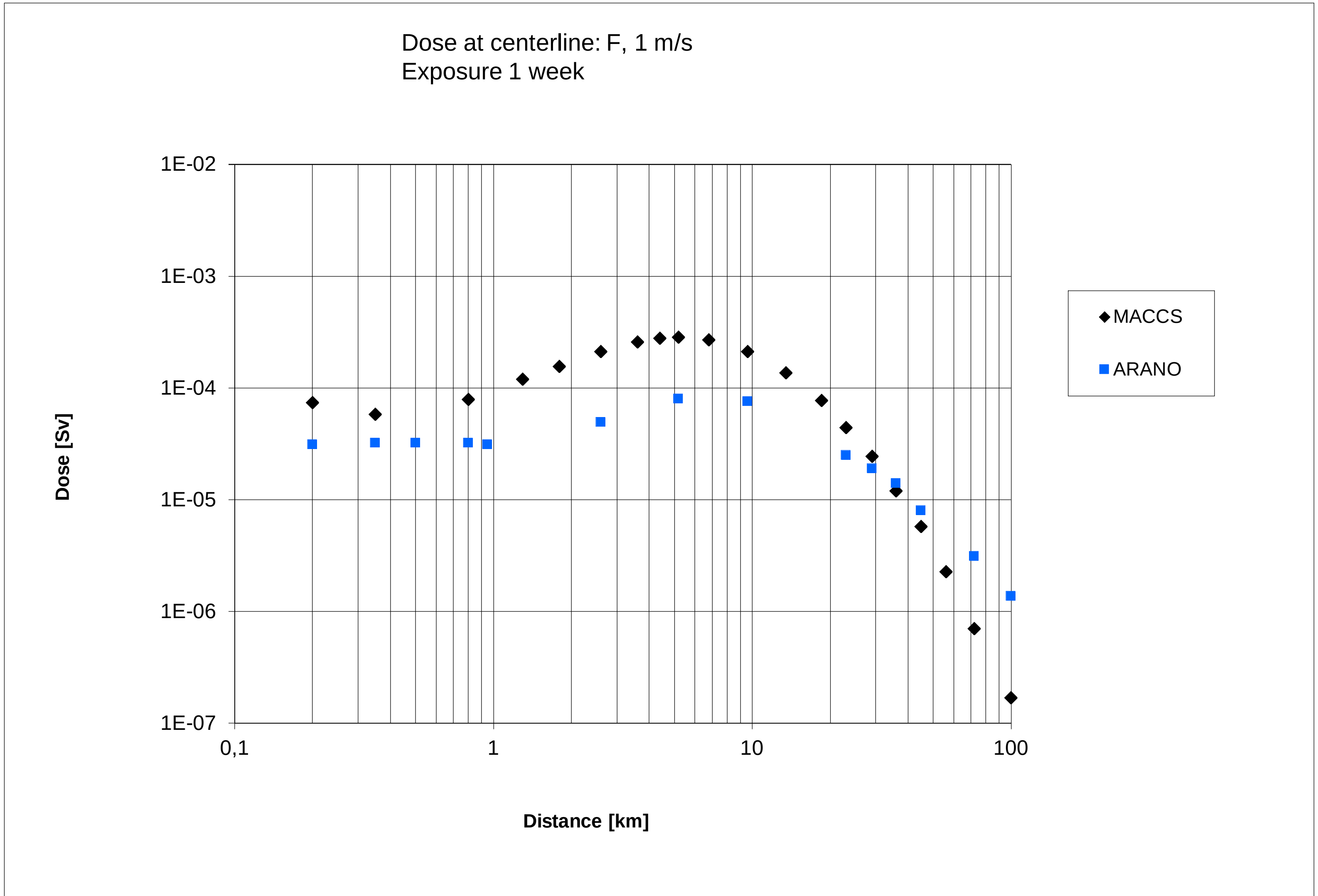
Single weather, Non-ingestion exposure pathways ('3')



- Cs-137
- Stability C
- 5 m/s
- Rain 5 mm/h
- 1 week exp.

- ARANO higher up to 2 km
- After 2 km, heavy rain seems to have scavenged a lot more in ARANO

Single weather, Non-ingestion exposure pathways ('4')



- Iodine
- Stability F
- 1 m/s
- No rain
- 1 week exp.

'BAD'

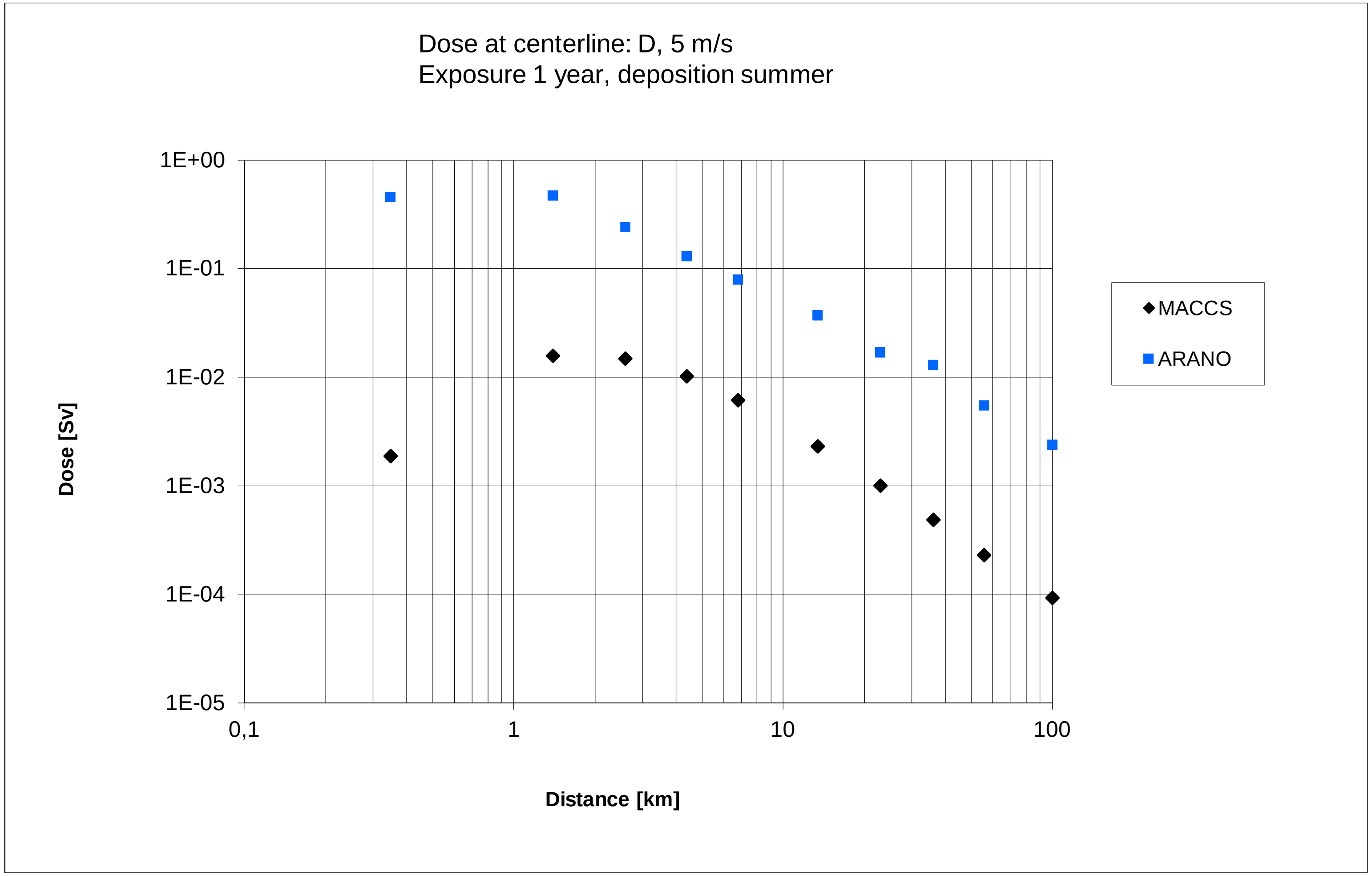
- ARANO lower up to 30 km in the stable condition

Single weather comparison runs, Ingestion exposure pathways

- Stability D, wind speed 5 m/s, no rain
- Consumption time 1 year, DC factors 50 a (adult)
- ARANO considers milk, meat, grain, green vegetables, roots
- Local (Finland) parameter values included in MACCS COMIDA2
- Some ingestion / single weather cases:

	Stability	Wind (m/s)	Nuclide (t ½)	Season
1	D	5	Cs-137 (30.17 a)	Summer
2	D	5	Cs-137	Winter
3	D	5	I-131 (8 d)	Winter
4	D	5	I-131	Summer

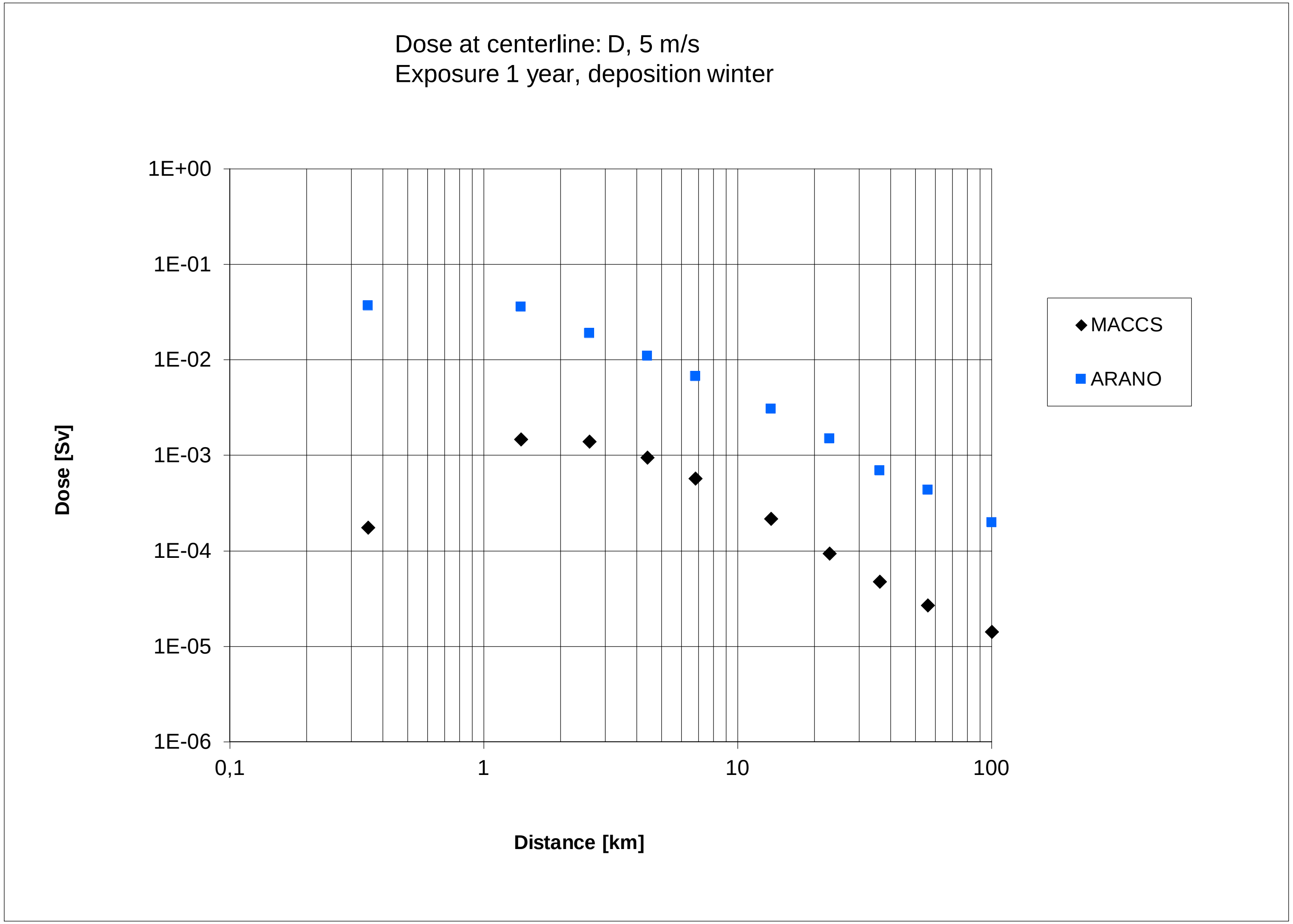
Single weather, ingestion pathways Cs-137 release, summer ('1')



- Cs-131 (half-life = 30.17 a)
- Stability D
- 5 m/s
- No rain
- 1 year consumption

- ARANO higher, mostly 10x

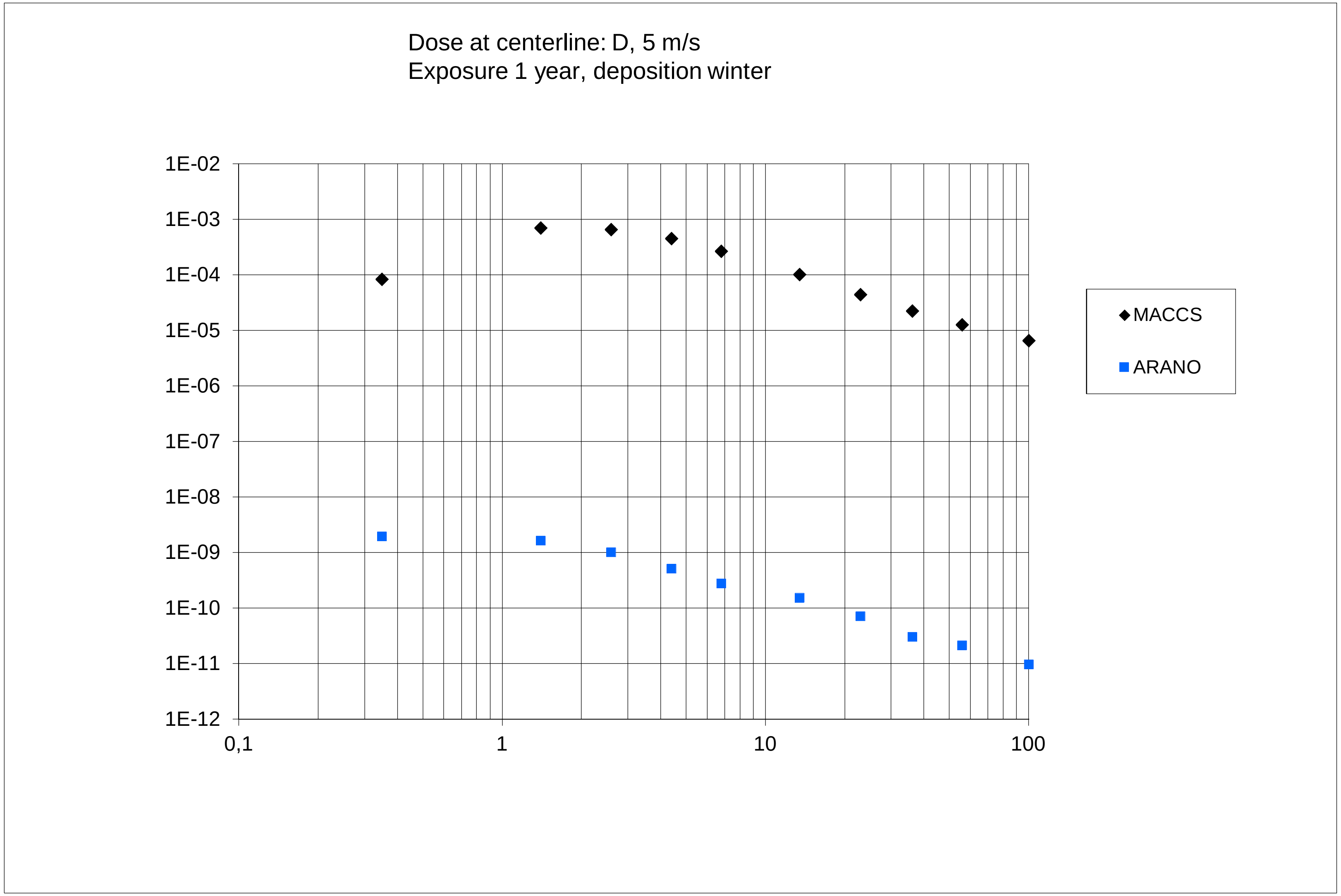
Single weather, ingestion pathways Cs-137 release, winter ('2')



- Cs-131 (half-life = 30.17 a)
- Stability D
- 5 m/s
- No rain
- 1 year consumption

- ARANO higher, mostly 10 m

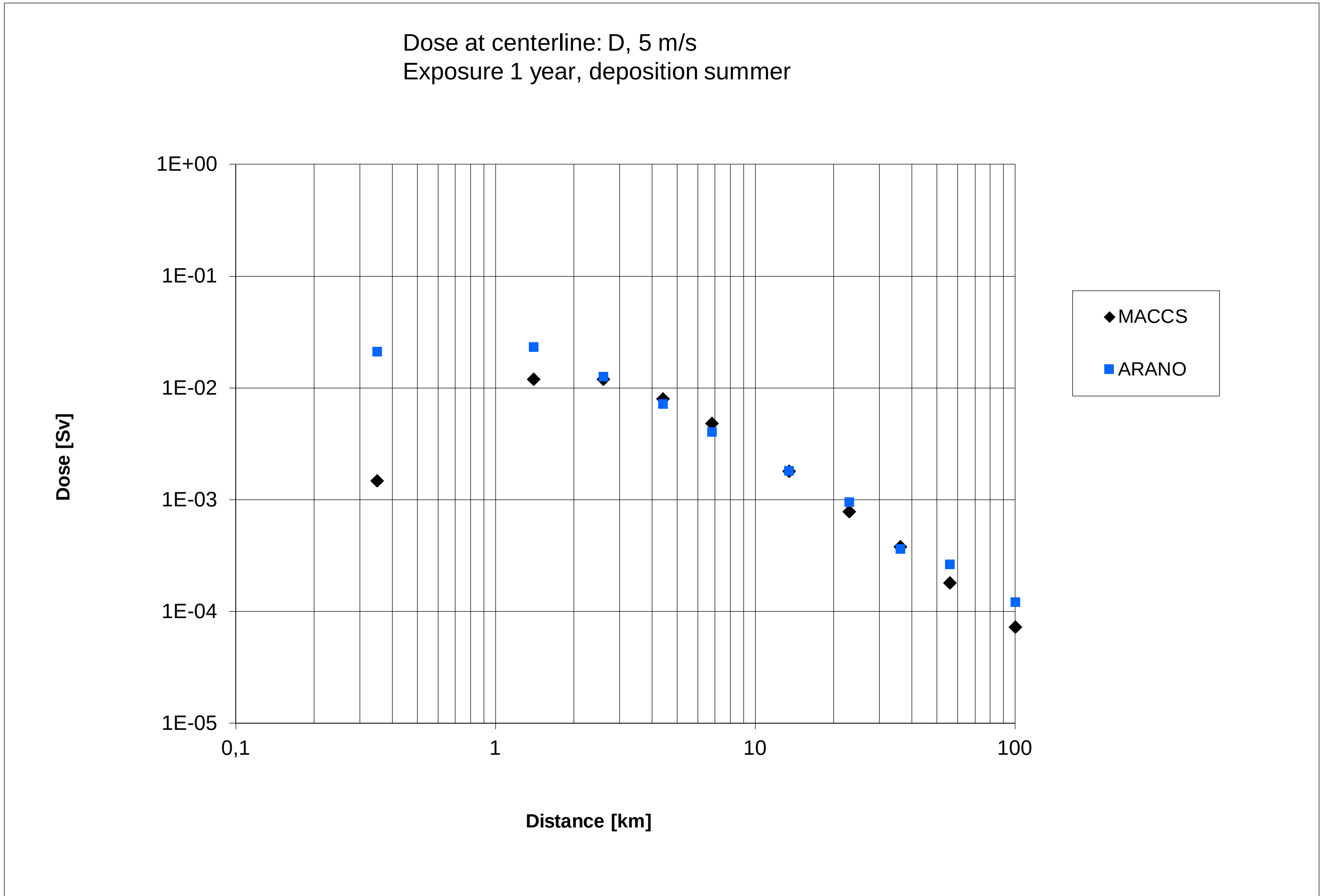
Single weather, ingestion pathways (winter) I-131 release; cow milk and meat dominating



- Iodine
- Stability D
- 5 m/s
- No rain
- 1 year consumption

- ARANO lower (1E6 x)
- Probably growing season not the same in the models?

Single weather, ingestion pathways (summer) I-131 release; cow milk and meat dominating



- Iodine
- Stability D
- 5 m/s
- No rain
- 1 year consumption

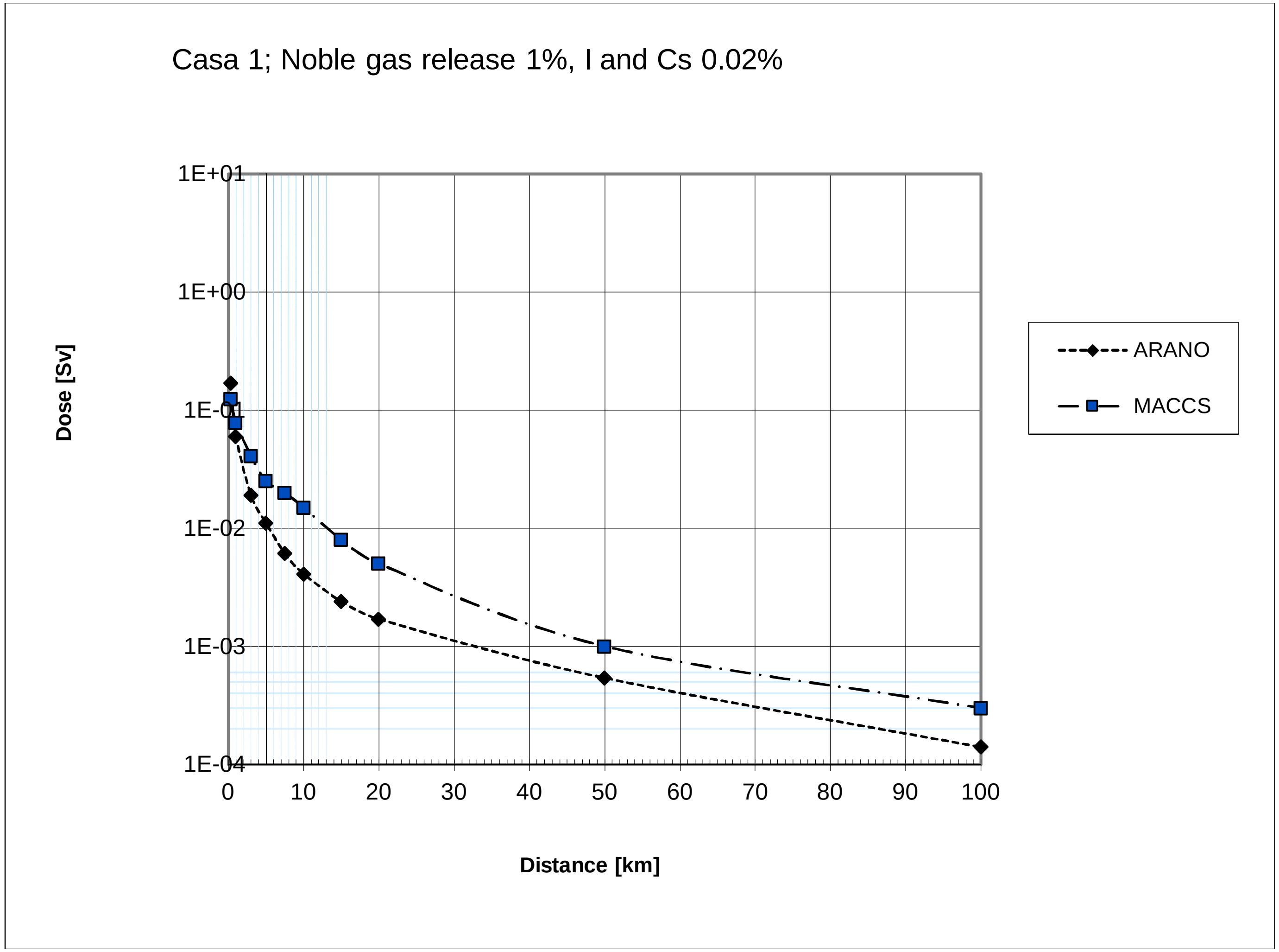
- ARANO higher at < 3 km and > 20 km

CCDF (one year weather) results, ’95 %’ Integration / consumption time 1 year

- Olkiluoto site, weather mast data (2009)
- CASA project source terms [Rossi, Ilvonen 2015] were used:
  - Case 1: ‘CASA1’, noble gases 1%, I-131 1000 TBq, Cs-137 100 TBq (Severe accident release limit in Finland)
  - Case 2: ‘CASA2’, noble gases 20%, iodine + caesium 2%
  - Case 3: ‘CASA3’, noble gases 100%, iodine + caesium 20% (‘No containment’)

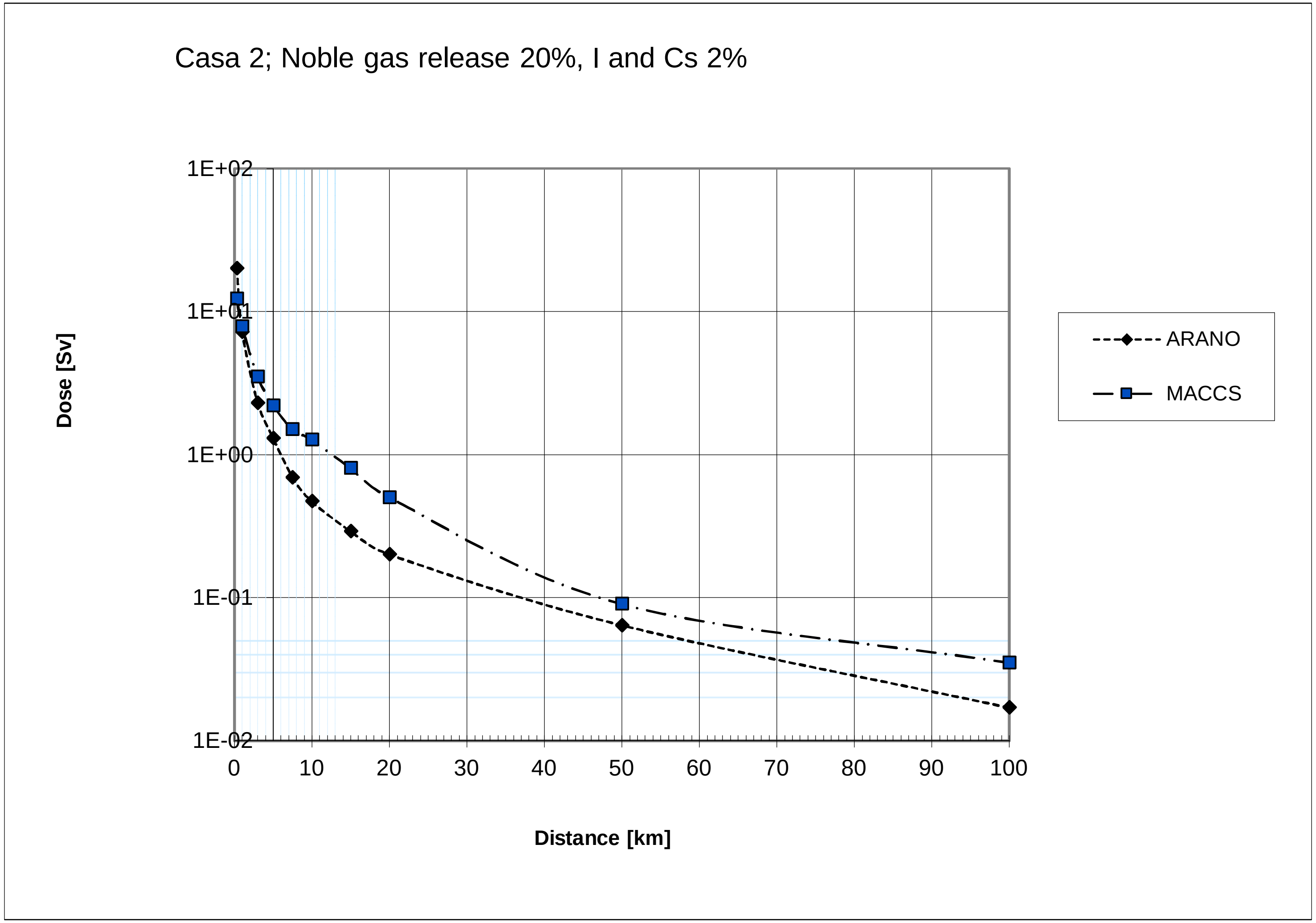
	Source term	Exposure path	Models
1	CASA1	Non-ingestion	ARANO, MACCS
2	CASA2	Non-ing.	ARANO, MACCS
3	CASA3	Non-ing.	ARANO, MACCS, VALMA
4	CASA1	Ingestion	ARANO, MACCS, VALMA

The dose of the 95 % fractile from the CCDFs, As function of distance, Non-ingestion paths, ’1’



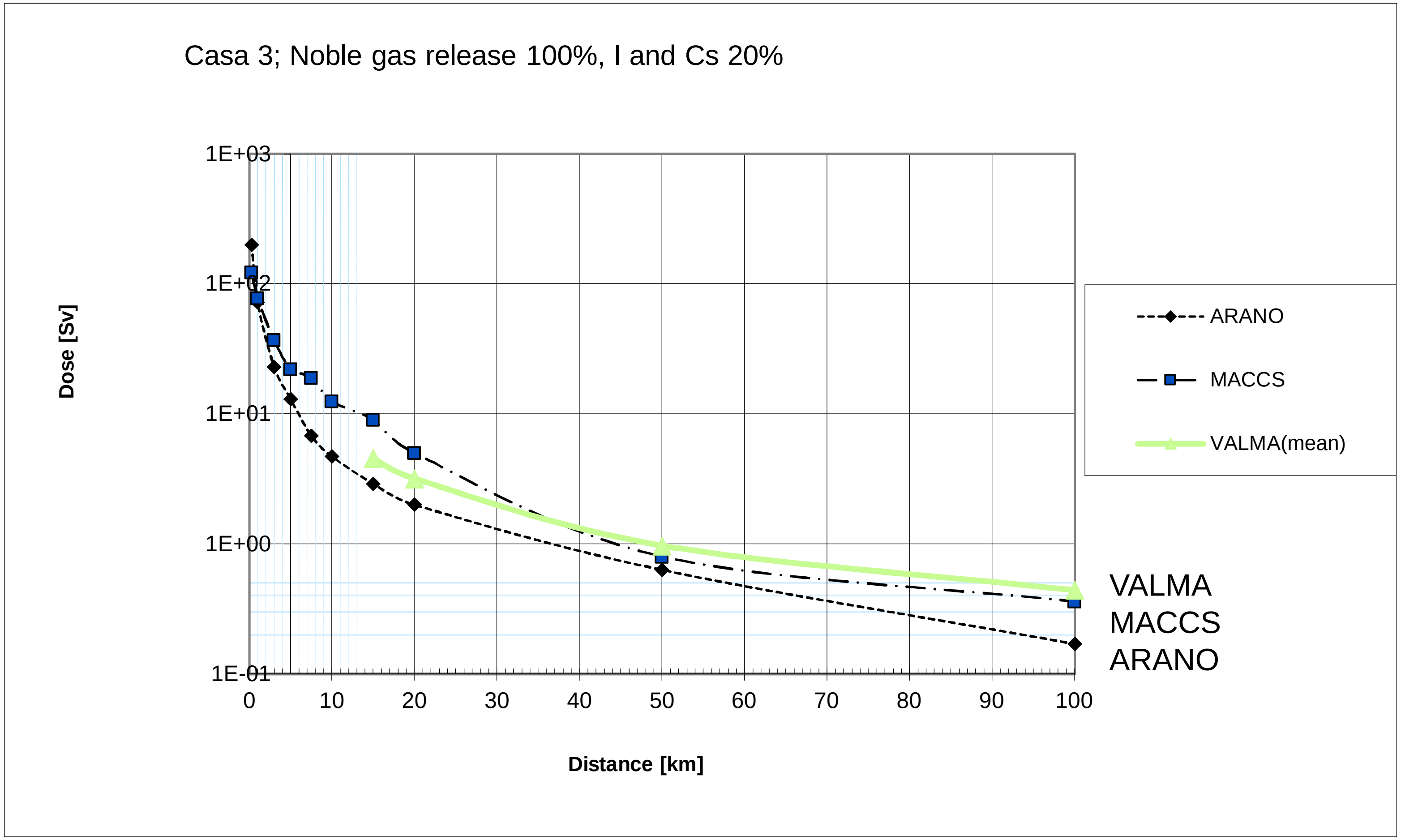
- Source term ’CASA1’
- One year integration for groundshine
- ARANO doses consistently lower than MACCS

The dose of the 95 % fractile from the CCDFs, As function of distance, Non-ingestion paths, ’2’



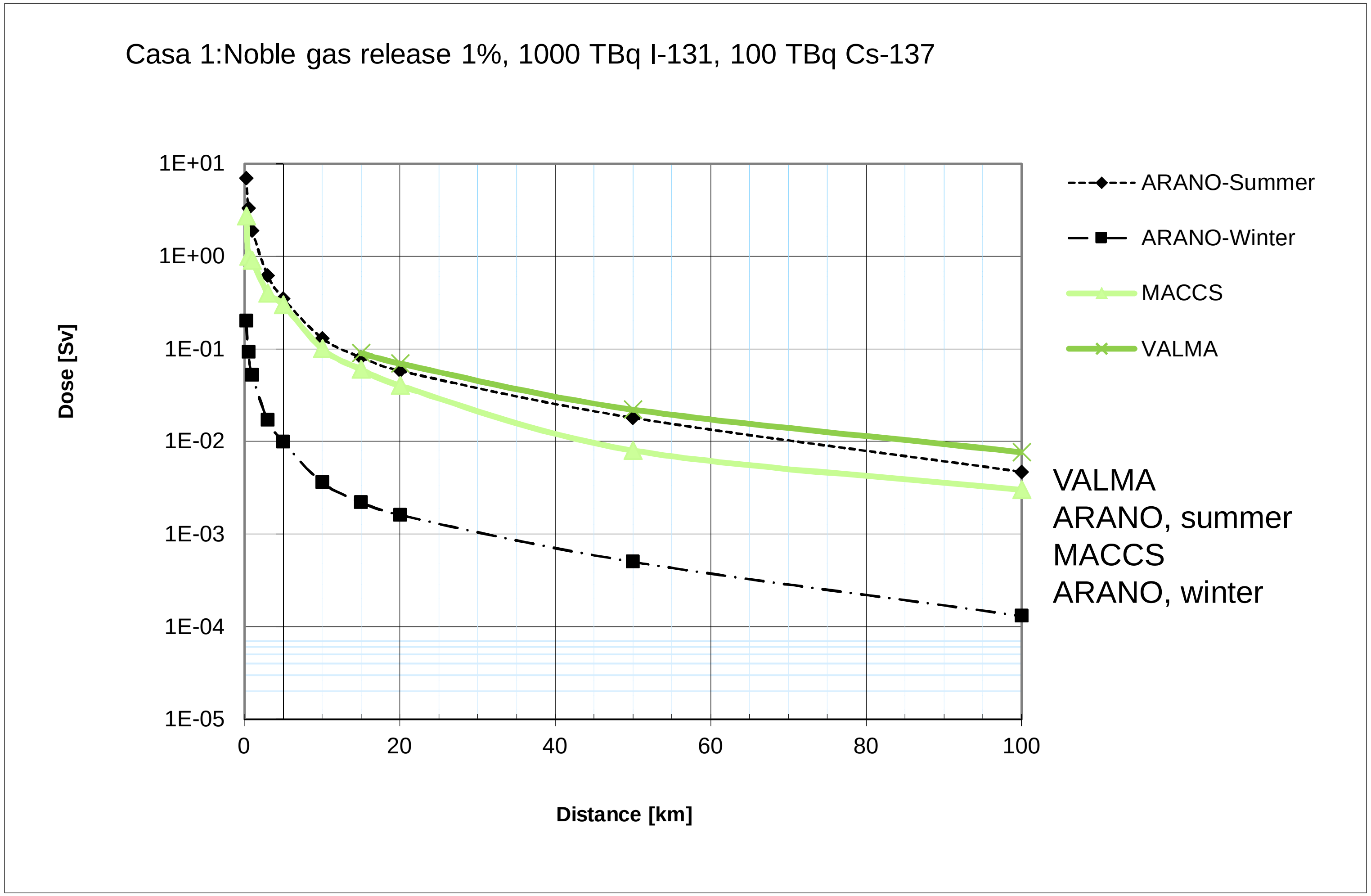
- § Source term ’CASA2’
- § One year integration for groundshine
- § ARANO doses consistently lower than MACCS

The dose of the 95 % fractile from the CCDFs, As function of distance, Non-ingestion paths, ’3’



- Source term ’CASA3’ (no containment)
- One year integration for groundshine
- VALMA available only 15 km and beyond in this case

The dose of the 95 % fractile from the CCDFs, As function of distance, Ingestion paths, '4'



- Source term 'CASA1'
- One year consumption
- VALMA only 15 km and beyond in this case

Comparison of ARANO, MACCS and VALMA -Conclusions on dose results

- Two kinds of comparisons were made:
  - Chosen single dispersion conditions
  - One year's weather data (measured hourly by met. mast)
- Compared were two kinds of doses:
  - Cloudshine + groundshine (1 week / 1 year) + inhalation
  - Ingestion doses
- ARANO typically predicts smaller dose values than MACCS.
- In most cases, ARANO predicts higher doses near the source than MACCS; for ingestion, difference can be either way
- Significant differences in single dispersion situations
- When the dose at e.g. 95% fractile is considered, the difference is at most less than a factor of three.
- Comparable dose estimates of VALMA predict smaller dose values than MACCS at distances up to 15 km.
- This comparison indicates that MACCS in many cases calculates conservative dose estimates?

Comparison of ARANO, MACCS and VALMA includes effects of weather source (VTT-R-00136-19)

- VALMA used SILAM-based meteorological data for Olkiluoto (2012)
- ARANO and MACCS were used with mast-based meteorology (parameters measured at the Olkiluoto NPP weather mast).
- VALMA can also be used with single-points measurements, but that is not the recommended use, if SILAM data is available.
- ARANO and MACCS differ in how they use the measured params:
- ARANO mixing height follows from the vertical profiles of the Kz model, and it is basically a function of atmospheric stability.
- MACCS uses only seasonal average mixing heights.
- ARANO uses wind speeds for the release height.
- MACCS wants wind speeds for its fixed reference height, and then calculates the needed speed for the actual release height from a logarithm formula.
- It is evident that the meteorological parameters alone could be responsible for significant differences in results.

Some problems with WinMACCS encountered at VTT

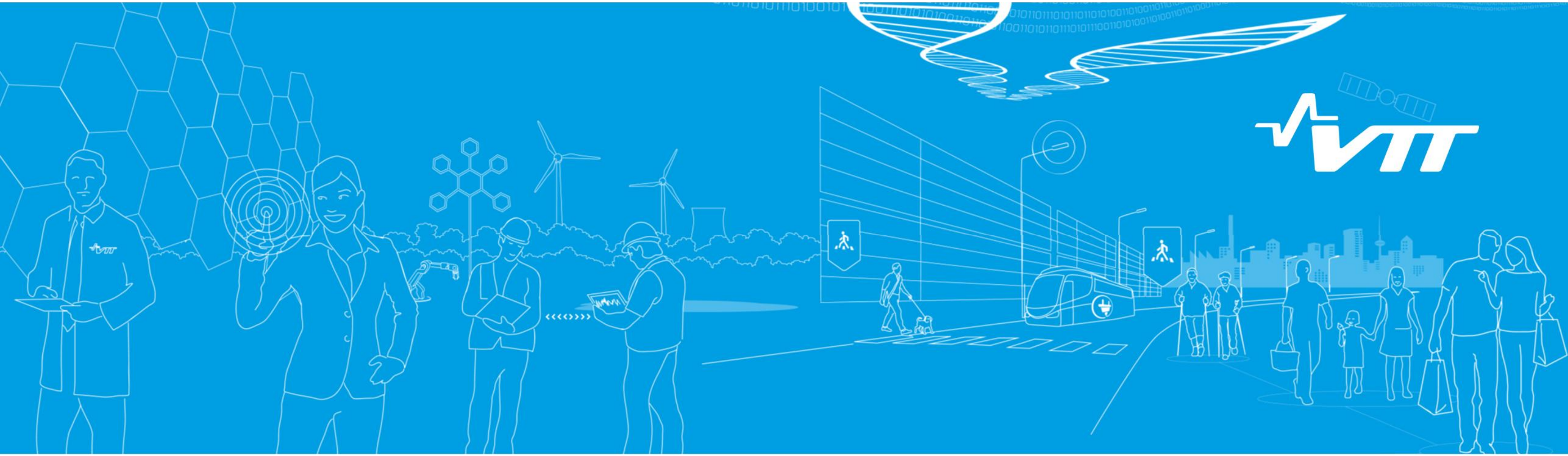
(Note: Maybe we didn't so far understand all the proper procedures.)

- Installation, upgrading of project input files:
  - 3.11.2 won't install ('Visual Basic 6.0 Setup Toolkit: Run-time error – method of object failed.')
  - Upgrading project inputs from 3.10.2 to 3.11.2 not successful
  - Type mismatch of the forms' numerical input fields (decimal symbol / digit grouping symbol?)
- Exposure pathways, integration times (cf. IAEA GSR Part 7, App. II):
  - Doses to fetus & tissue (0.5 cm under skin) needed
  - Exposure integration time 10 h is needed
  - What is the fidelity of predictions in the very near field (< 500 m) ?
- Practical: Batch running, extraction of results
  - Should we use cyclic run to easily get results for a number of exposure pathways
  - Should we extract the results for further use from the result file manually or by writing a dedicated code

VTT creates business from technology

From here on:

You find also some ’backup slides’ (Presentation in longer form)



VTT Nuclear Safety (Finland)
- Dispersion and Dose Assessment

IMUG Meeting, 10 June 2019, NRC

Mikko Ilvonen & Jukka Rossi, VTT

Main contents of presentation

1. Nuclear power in Finland
2. Nuclear fission research at VTT Nuclear Safety
3. ARANO short-range level 3 PSA code by VTT
4. VALMA long-range code by VTT
5. Fukushima modelling attempts
6. Dose probability distributions up to 300 km
7. Ingestion pathways for Nordic agriculture
8. EPZ right-sizing methodology
9. Code comparisons ARANO-VALMA-MACCS

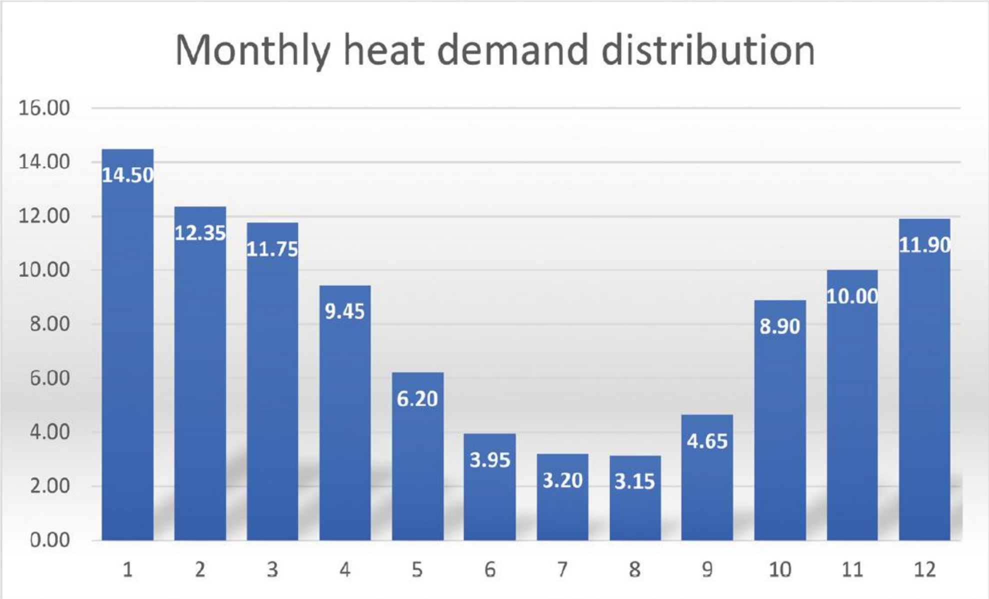
Nuclear power in Finland (Regulator: STUK)

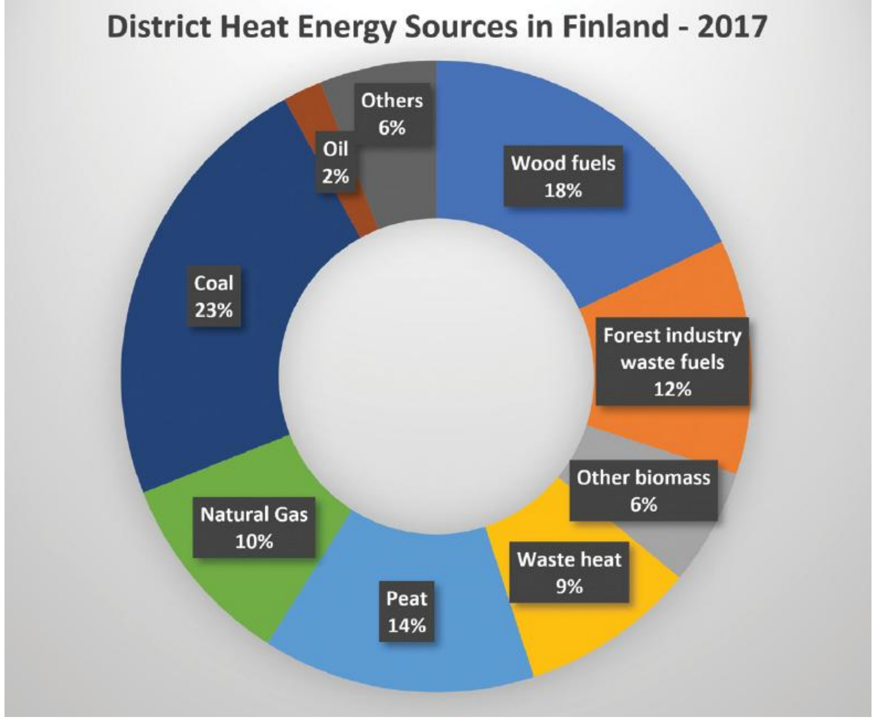
- Loviisa (owned by Fortum)
  - 2 x Soviet VVER-440
- Olkiluoto (TVO)
  - 2 x Swedish BWR
  - French EPR expected online 2019
    - Many delays, e.g. piping vibration (2018)
    - Got operating license in early 2019
- Hanhikivi (Fennovoima)
  - Russian VVER-1200 planned
    - Application for construction permit (2015)
    - Still to be completed by Fennovoima
    - STUK assessment in 2019?
- VTT (green) in Espoo, near Helsinki

Map from Wikipedia

Nuclear power plants in Finland (**view**)
Active plants
Planned plants

Future: Nuclear district heating in Finland?





- (Source of graphics: Partanen 2019, Nuclear DH in Finland)
- Several cities have expressed their interest in nuclear DH
- In February 2019, the Finnish Parliament voted 170-14:
- To pass the law for banning coal in energy use by 1st May 2029.
- Schedule too tight for SMR heat?

Coming update of Nuclear Energy Act & Decree; Potential for more SMR-tailored licensing? (1)

- Source: J Louvanto, MEAE (Finnish Ministry of Economic Affairs and Employment) & M Tuomainen (STUK)
- Going to be a big, long-lasting process (complete: 2024 ?)
- Considered in a group involving ministry, STUK (regulator), universities and energy industry
- SMRs kept high on the agenda
- Topics: Site approval, type approval, waste management, security
- Current licensing was made considering large LWR (but some exceptions for small research reactors)
- Political decision on SMR needed: overall good of society?
- STUK resources for SMR activities are very limited
- Same level of safety (consequences) is expected and must be demonstrated

Coming update of Nuclear Energy Act & Decree; Potential for more SMR-tailored licensing? (2)

- Source: J Louvanto, MEAE (Finnish Ministry of Economic Affairs and Employment) & M Tuomainen (STUK)
- One alternative for the new licensing model:
  1. Design certification (by vendor application)
  2. Site approval separately
  3. Operating license, concentrating on:
     - Changes to certified design
     - Licensee's performance
  4. Waste management by one actor on national level
  - Unmanned power stations, remote operation?
  - Security, cybersecurity, safeguards?
  - STUK participates in WENRA discussion to include SMRs in harmonization & in IAEA SMR Regulators' Forum

Areas in VTT nuclear fission research

- **Plant safety and performance**
  - Deterministic safety & engineering analyses
    - Fuel and reactor physics
    - Thermal hydraulics & integrated analyses
    - Accident and transient analyses
    - Severe accident management
    - Radiological release analysis
    - Fire and evacuation safety analysis
  - Probabilistic safety analysis (PSA)
  - Structural safety and integrity of reactor circuit and structures
  - Material performance assessment
  - Systems engineering
  - Automation (I&C) validation and verification
  - Human factors engineering, control room
  - Organization, safety culture
  - Remote handling

TVO, Olkiluoto NPP site

VTT Triga Mark II RR 1962-

- **Waste management and geological disposal**
  - Performance analyses of technical and natural barriers of repositories
  - Technology development of engineered safety barriers

- **New generation reactors and fuel cycle**

VTT Centre for Nuclear Safety (CNS)

CNS research teams (about 20 people each):

- NPP materials
- Nuclear waste management
- Reactor physics
- Reactor dynamics analysis
- Plant behavior modelling
- CFD simulations
- Iodine laboratory

Nuclear & the environment: VTT research topics (1/2)

- Radioactive source term:
  - Transfer of radionuclides inside of NPP and effects on exposure
  - Plume rise
- Different ’modes’ of calculation:
  - Releases from normal NPP operation
  - Accidental releases from NPP
  - Licensing, PSA-3, emergency preparedness
- Computational tools:
  - VTT & NRC tools, evaluation of dose calculation models
- Applications:
  - Level 3 PSA
  - NPP siting
  - Old NPPs, EPR, SMRs, SNF handling, etc.

Nuclear & the environment: VTT research topics (2/2)

- Regulations (supporting STUK):
  - Limit values / 100 TBq Cs-137 release
  - YVL Guides contributions, etc.
- Nuclear waste:
  - Transportation risk analyses
  - Disposal of nuclear waste
  - Clearance of radioactive material
  - Decommissioning of facilities
- Biospheric transport
  - Radioactive deposition and consequences
  - Computer codes for biospheric analyses

VTT-developed dose assessment models

- **ARANO:** (PSA3 code): used in siting studies in 1975-76, applicable at short ranges from source (10-20 km, in some cases max 100 km)
- **ROSA:** used at Finnish NPPs since 1991, based on ARANO, weather data at 10 min intervals; calculation up to 20 km radius; still used at Olkiluoto?
- **TRADOS:** 1983; 'emergency version' for Unix in 1992; long-range dispersion model (thousands of km); dispersion by FMI, doses by VTT
- **SILAM:** VTT participation in development in the 1990s
- **VALMA:** (first demonstration in 1998); user interface in Windows
  - Dispersion based on weather mast data or (preferably) SILAM
- **DETRA:** biospheric transport (deposition > foodstuff > humans) of radionuclides & related dose assessment

ARANO short description

- **ARANO** (Assessment of radiological consequences of atmospheric radioactive releases), developed at VTT in the 1970's
- Dispersion: 'Traditional' straight-line Gaussian
- Initially used for nuclear power plant siting studies.
- Has been used to estimate effectiveness of different countermeasures.
- Has been used by VTT to support STUK in various safety assessments for constructing new power plant, dismantling a research reactor, and for disposal site
- Functionality comparable to MACCS (Sandia / NRC):
    - Atmospheric transport and deposition onto the ground
    - In addition to a single dispersion case statistical effect of variability in weather
    - Dose pathways: cloudshine, groundshine, inhalation, ingestion, deposition onto skin
    - Protective actions during emergency, intermediate, and long-term phases
    -
    - Offsite consequences:
        - Doses to individual and population, health effects
        - Economic costs, land contamination

ARANO (Assessment of Risks from Accidents and Normal Operation of NPPs)

- first version in 1977 for siting studies of NPPs
- atmospheric dispersion, dose calculation
- dispersion model developed with the Finnish Meteorological Institute (FMI)
- exposure pathways: external radiation from the plume and fallout, inhalation, ingestion of food
- verification in the code comparison exercises 1982 and 1994 (with MACCS, COSYMA, OSCAAR,..)
- applied to various studies for authorities, power utilities, etc.
- input/output files - no user interface

Pasquill model (general)

$$\chi(x, y, z, t) = q_0(t - x/u_H) \frac{1}{2\pi\sigma_y\sigma_z u_H} \exp(-\frac{y^2}{2\sigma_y^2}) \cdot$$

$$(\exp(-\frac{(z-H)^2}{2\sigma_z^2}) + (\exp(-\frac{(z+H)^2}{2\sigma_z^2}))$$

K_z model for vertical dispersion (ARANO)

$$(\frac{\partial C_z(z,t)}{\partial t})_m = \frac{\partial}{\partial z}[\ K_z(z)\frac{\partial C_z(z,t)}{\partial z} - v_d C_{zm}(z,t)\ ]$$

Effect of wet deposition on the plume

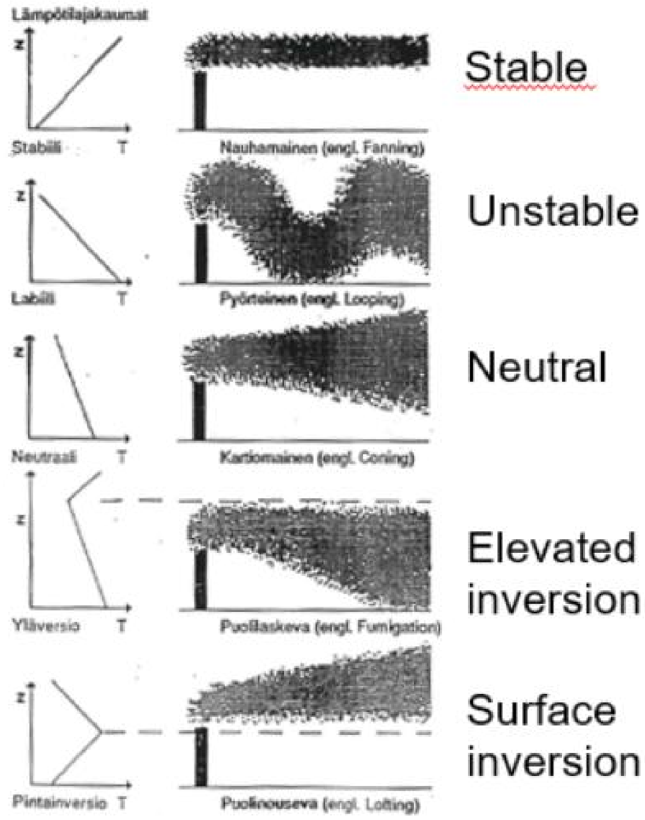
$Q/Q_0 = e^{(-\Lambda \cdot x/u)}$

Λ is washout coefficient (7E-5…5E-3 s^{-1})

- K_z (z) = coefficient of turbulent transfer
- V_d = dry deposition velocity (zero for gases)

ARANO cloudshine dose assessment

- Not using the uniform semi-infinite cloud approximation
- Near the release source, the size & shape of the plume may differ substantially from that approximation
- Cloudshine from actual shape of the plume
  - Algorithm is based on pre-calculated dose rate files for successive stages of the evolving Kz vertical profile
  - Wind meandering in longer duration releases accounted for



ARANO: SOURCE TERM

1. Define the release of the isotopes in Bq or
2. Give the reactor inventory in Bq and the release fraction for each element group.

Element group	Nuclides
1. Noble gases	Kr, Xe
2. Halogens	I, Br
3. Alkali Metals	Cs, Rb
4. Chalcogens	Te, Sb
6. Platinoids	Ru, Rh, Pd, Mo, Tc, Co
7. Lantanides	La, Zr, Nd, Nb, Pm, Pu, Pr, Y, Cm, Am
8. Others	H, N, C, Ar, Cr, Mn, Fe, Zn, Ag

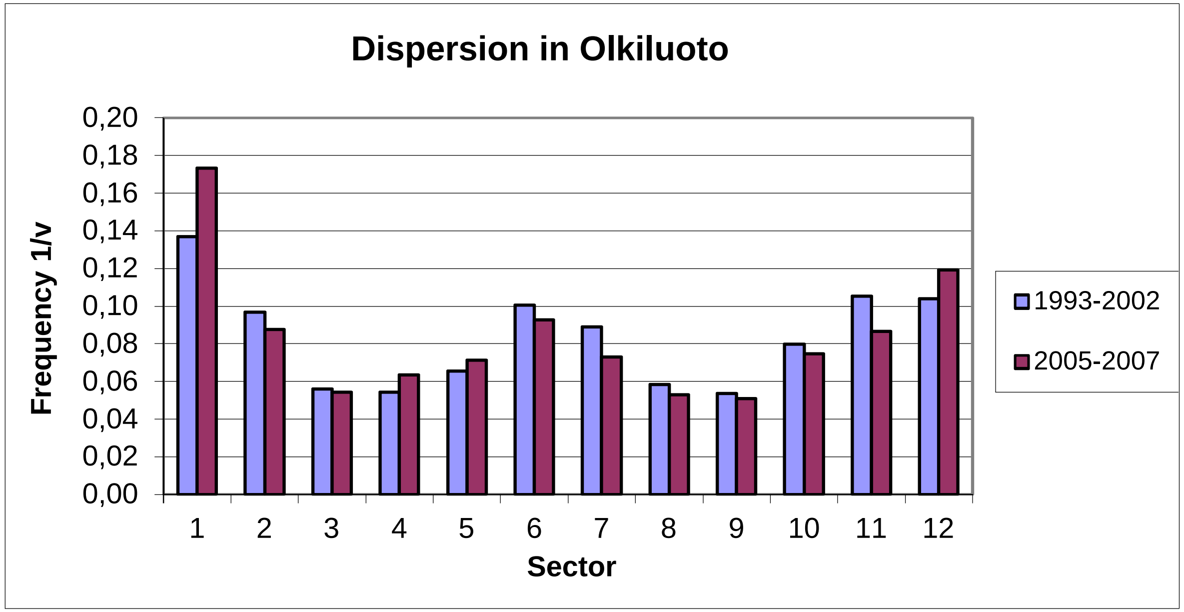
Inorganic / organic iodine compounds

DEFINE
- start and end time of the release (relative to shutdown)
- warning time (time interval between the predicted release and the real release)
- effective release altitude (plume rise separately)

ARANO: DEFINE WEATHER

- single dispersion case (Pasquill stability, wind speed and direction, rain)

- if long term weather data available, define distribution separately, usually hourly data covering several years from the release point (meteorological mast at the power plant) is used



Frequencies of dispersion sectors in Olkiluoto, time periods 1993…2007.

Countermeasures available in ARANO

1. Short-term measures
- sheltering (against plume and groundshine)
- evacuation (two group at two distances)
- iodine tablets for thyroid blocking (affects only the thyroid dose)

- no dependence on dose criterion; normally based on the measures to be done inside emergency zones (0…5 km, 5…20 km)

Purposed for the early phase of an accident

2. Long-term measures
- relocation
- land decontamination
- ban on food ingestion

- criterion based on contamination level or dose (groundshine, ingestion) during certain time interval

Purposed for the intermediate or late phase of an accident

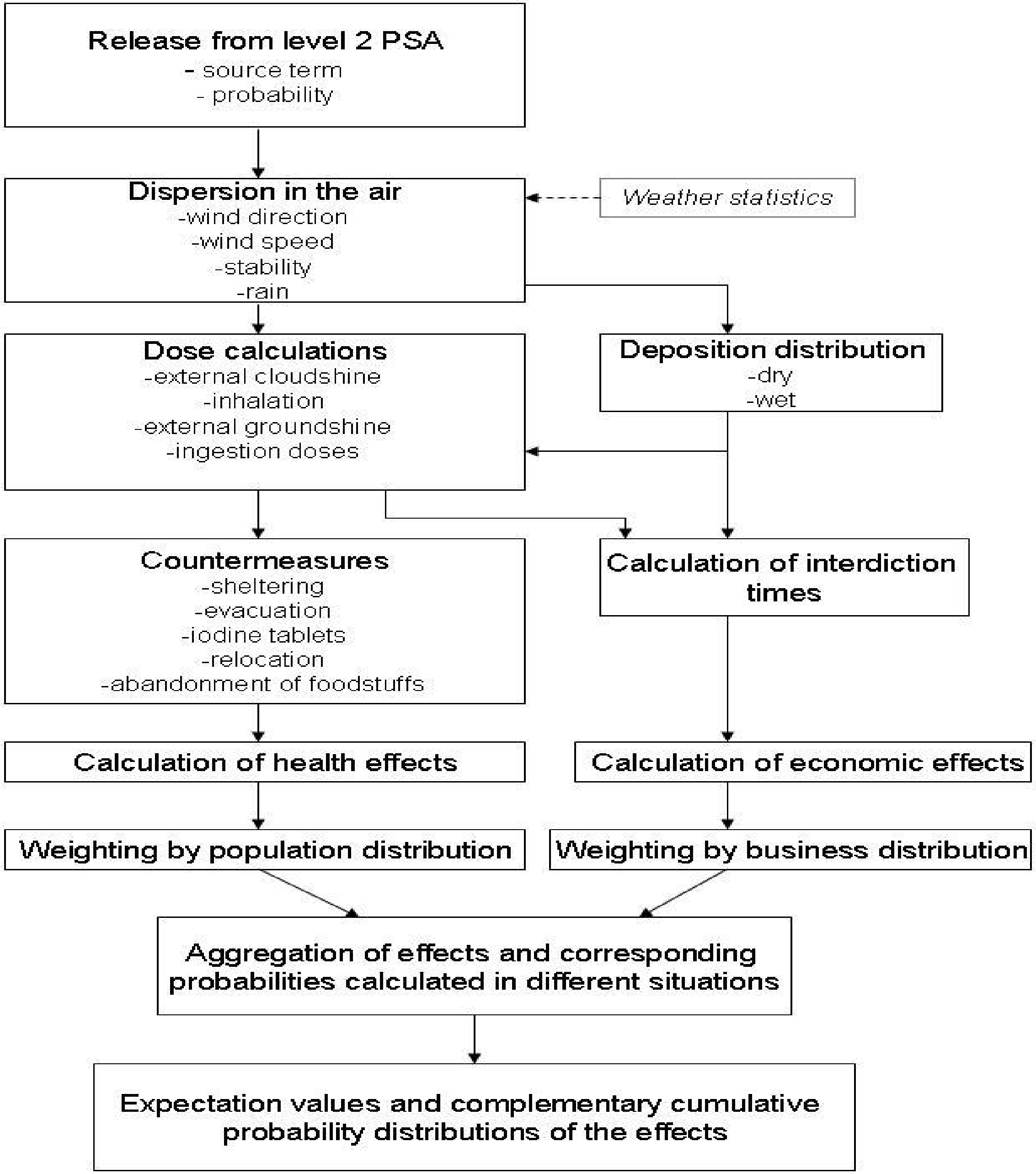
Health effects

- In ARANO the effect function type may be linear, acute or step

Usually early health effects are based on the acute or step function type and late health effects are assumed to be linearly depended on the dose.

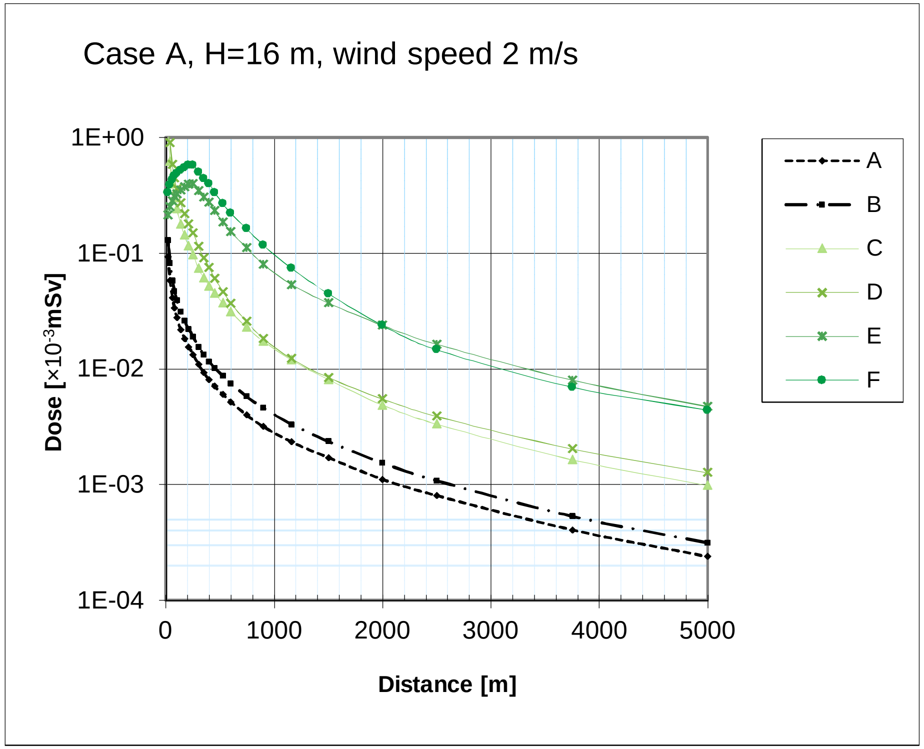
- The effective dose threshold of 1 Sv (step) can be employed for assessment of the number of radiation illness cases.
- The number of the early fatalities can be calculated using a dose response relationship in which the effective dose of 2 to 5 Sv (acute) causes the probability of early fatalities to increase from 0 to 1.
- For late effects a linear dose-response function can be used. The number of the fatal cancers can be calculated with a risk factor of 0.05 cancers/manSv.

The flow chart of the ARANO computer code



Samples of ARANO results

Sample Fir1 release (VTT research reactor) Triga Mark II

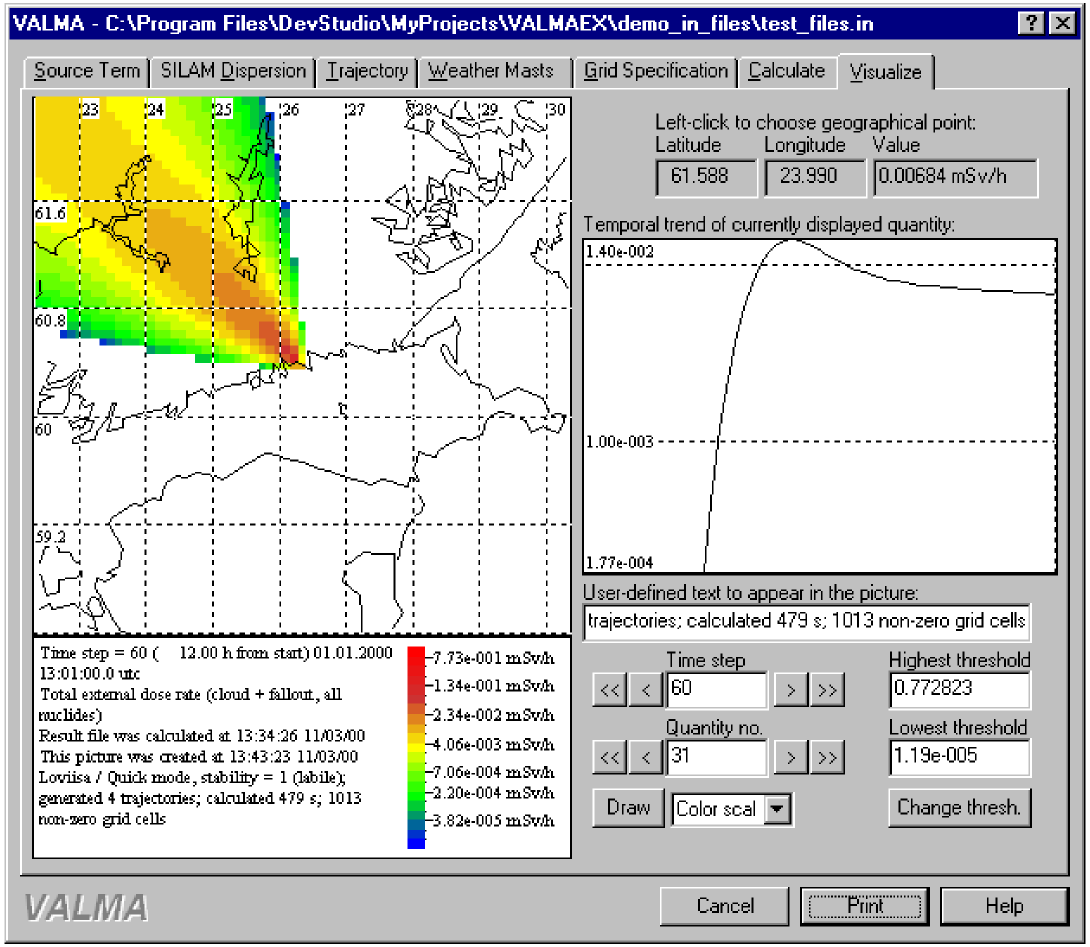


Dose in the Pasquill dispersion conditions.

- ARANO works fine for near field
- Stable conditions E, F have maxima at appr. 200 m

- Note: Scaling by power would practically appr. multiply the doses by a constant factor

VALMA long-range model



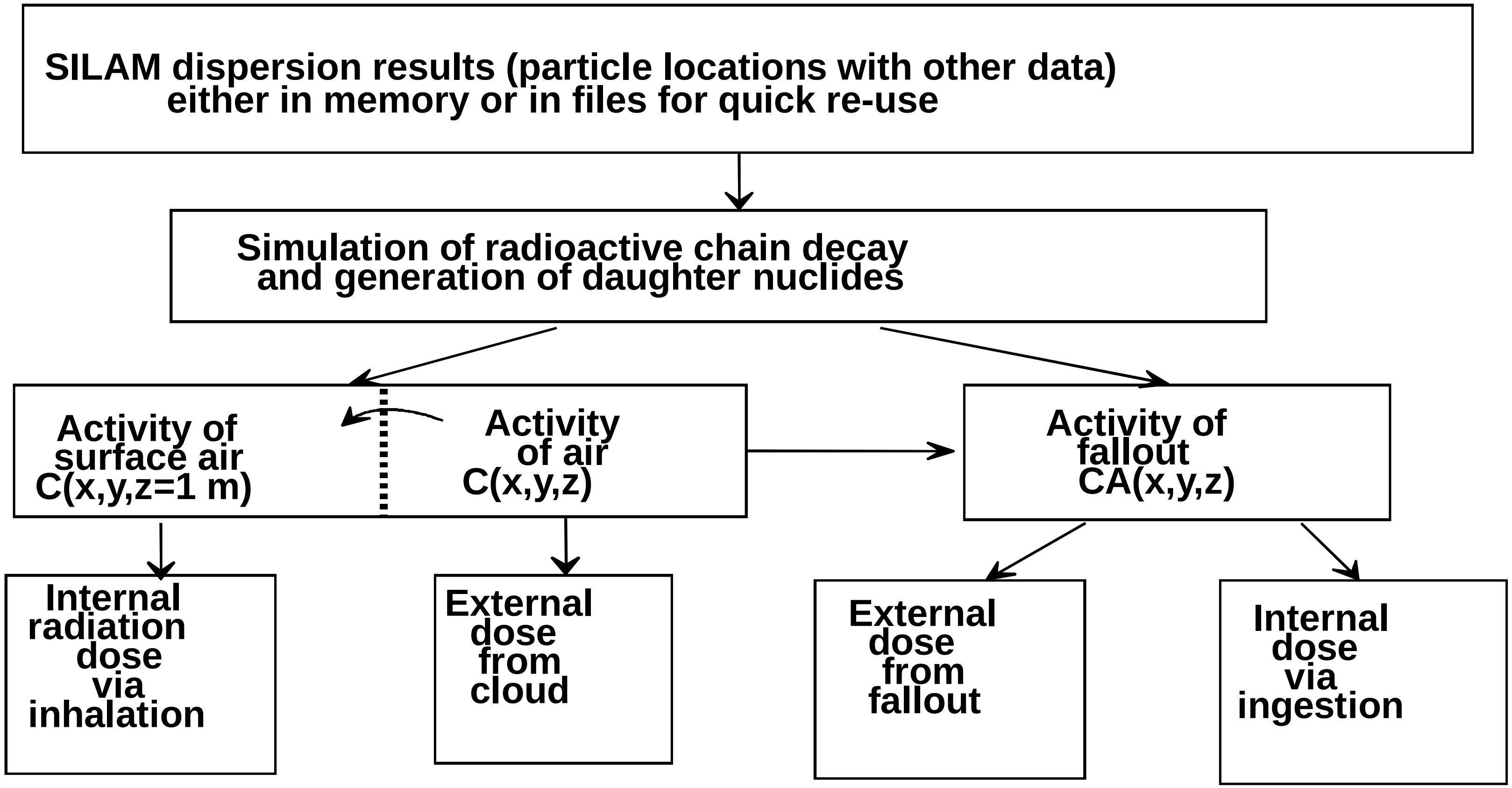
- Weather data from NWP (through SILAM), or from mast measurements
- Example above: release at loviisa NPP, using mast-measured weather data
- External doserate at 12 h after start of release (map) & temporal trend at chosen point

Important variable assumptions in VALMA dose assessment

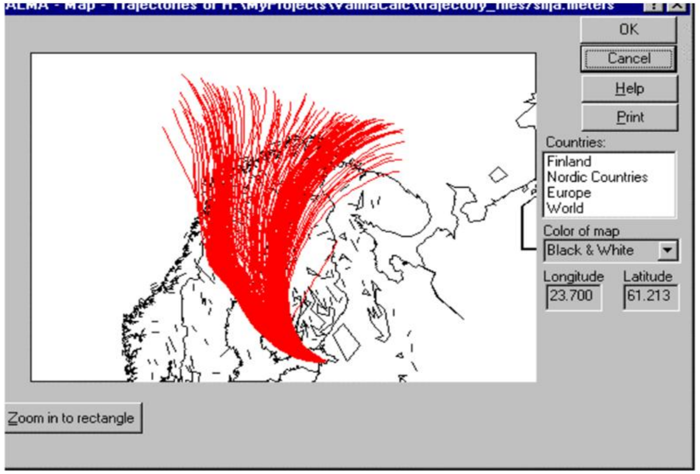
- **Start and end time of release** (from reactor SCRAM)
  - § Release rate may be a different function of time for each nuclide. In the VALMA model, these temporal functions can be varied arbitrarily within the time period for which trajectories were calculated (period of potential release).
- **Release height**
  - § Release rate is also a function of height, according to the escape route and physical factors affecting potential cloud rise.
- **Released activity**
  - § Total released activity per nuclide, usually reference to the time of SCRAM. In VALMA, these amounts can be easily varied by element group or by single nuclide.
  - § Measured activities (reference to each measurement time point) can be used.
- **Result quantities include radiation doses from several exposure pathways**
  - § External and internal doses & external dose rates must be calculated for several time points and using several different integration times
  - § * VALMA displays default result quantities (e.g. external dose rate) and others can easily be chosen for display.
- **Predicted results can easily be transfered to other emergency organizations**
  - § In emergency preparedness exercises, web pages (access control) are used for transfer

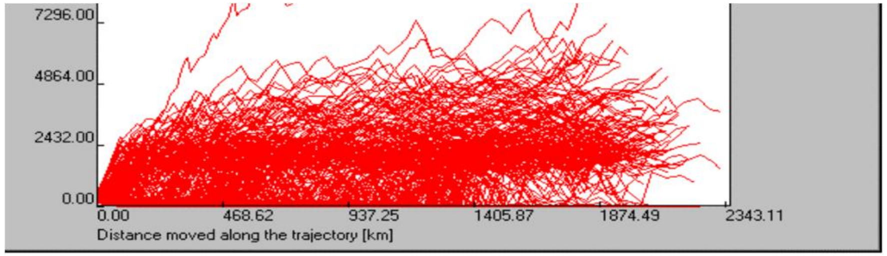
Dose assessment in VALMA

- The assessment of radiation doses is in many ways coupled with the real-time prediction of dispersion.
- The VALMA calculation system makes it possible to produce predictions of dispersion and doses that range from rough but fast to slower but more accurate.

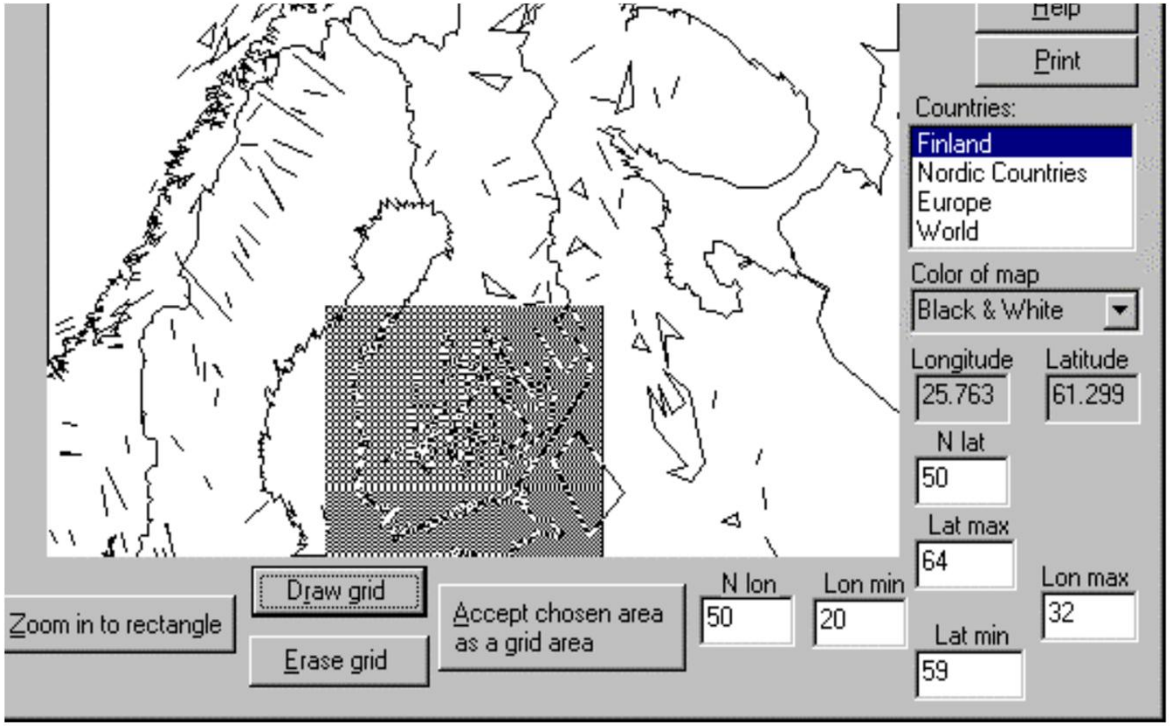


Map View and Side View of SILAM particle trajectories in VALMA

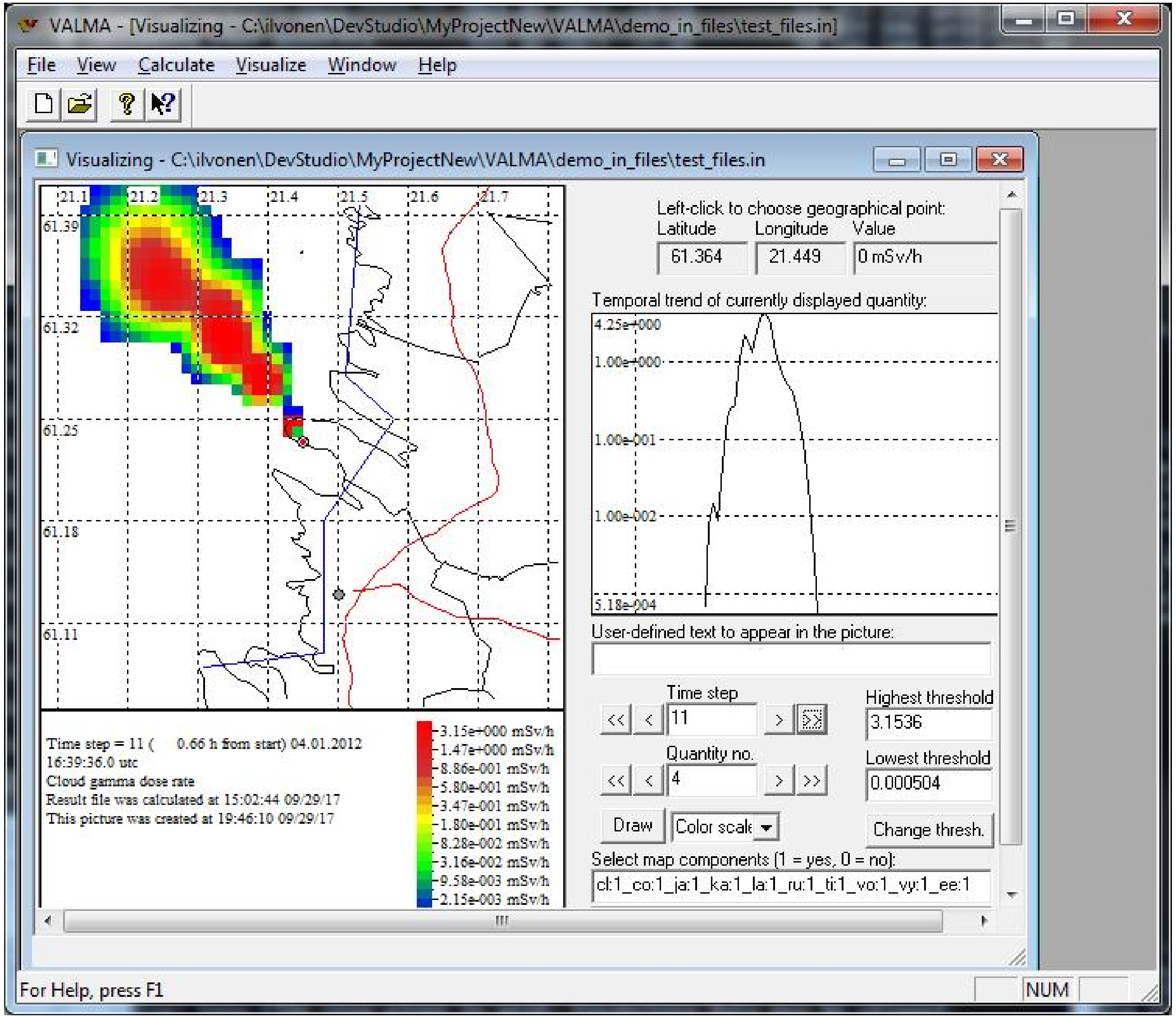




Geographical grid for result quantities in VALMA

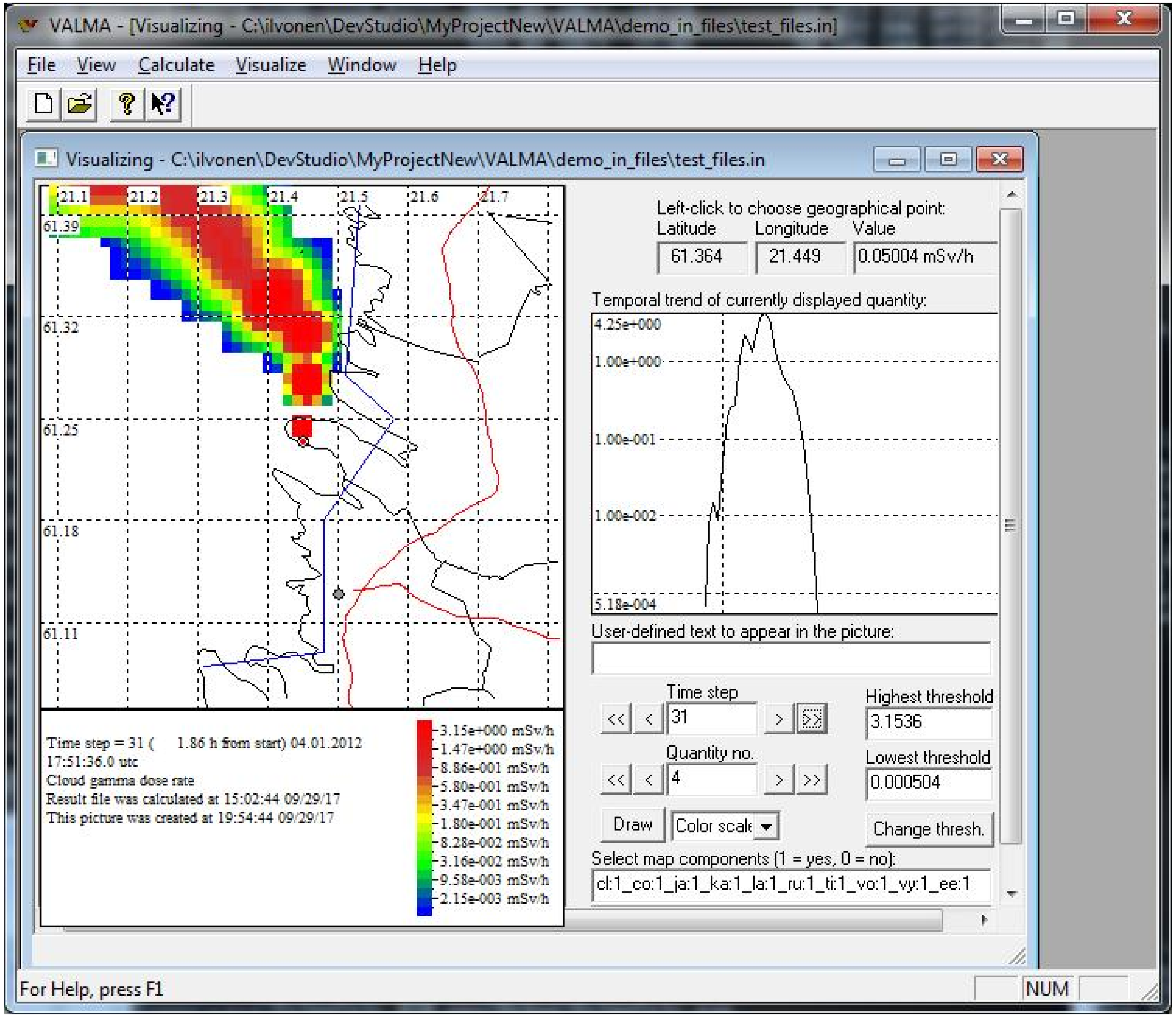


Bigger release VALMA results, 1/4, (cloudshine dose rate, 40 min from start)



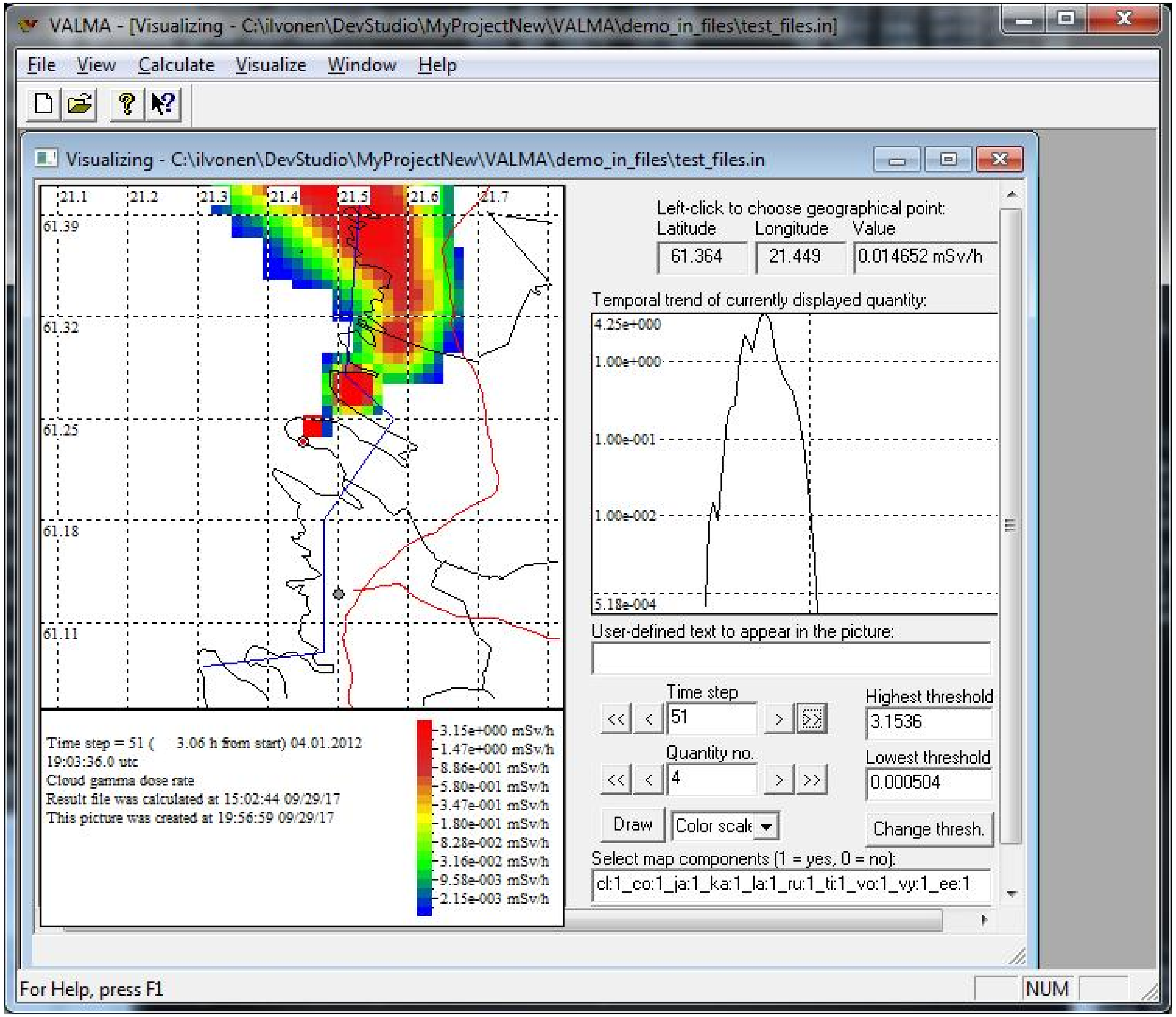
- One colored square is appr. 800 m x 800 m
- Map area is appr. 40 km x 40 km
- Olkiluoto in the middle
- City of Rauma marked with grey
- Wind speed seems appr. 8 m/s

Bigger release VALMA results, 2/4, (cloudshine dose rate, 1 h 52 min from start)



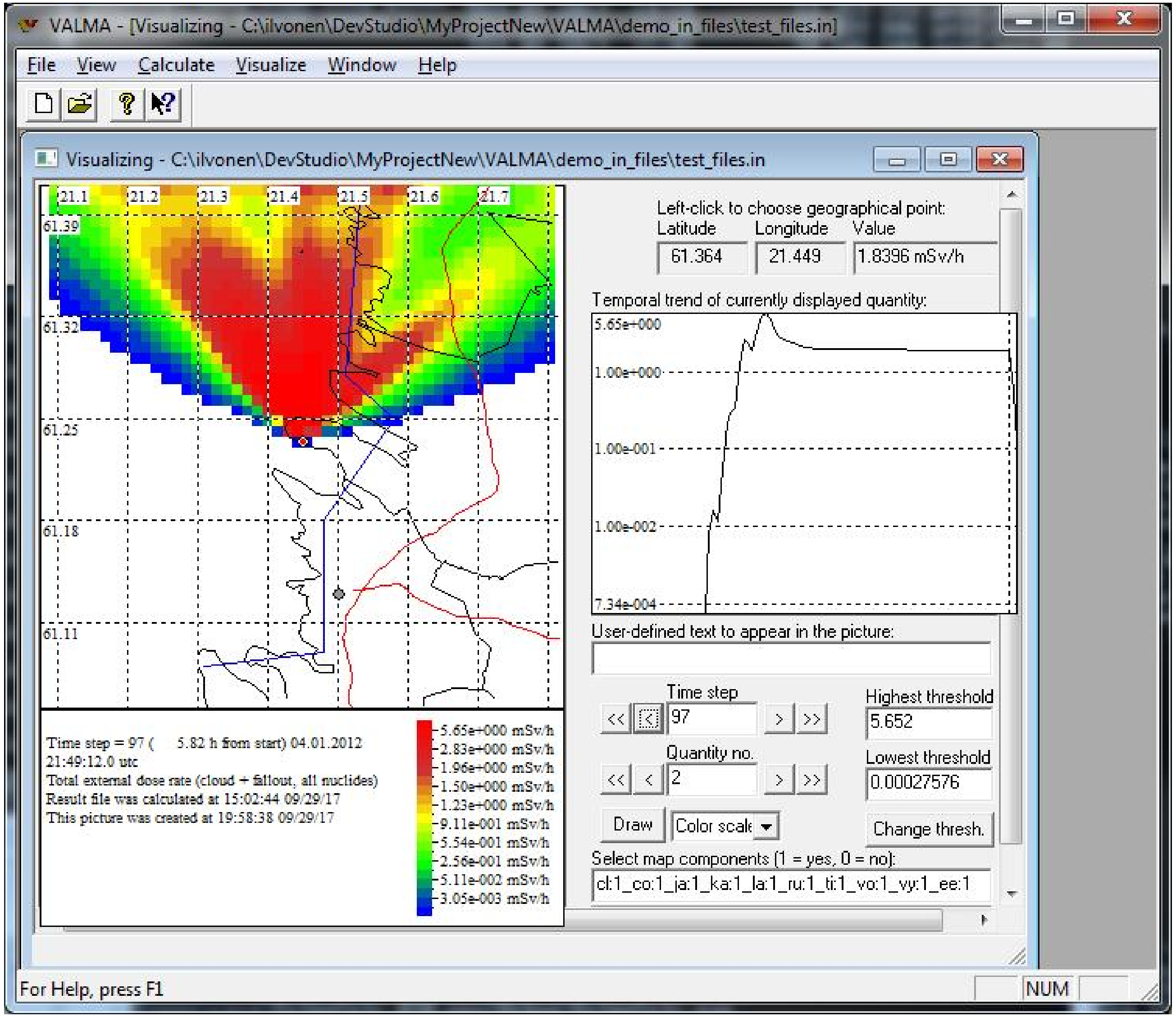
- One colored square is appr. 800 m x 800 m
- Map area is appr. 40 km x 40 km
- Olkiluoto in the middle
- City of Rauma marked with grey

Bigger release VALMA results, 3/4, (cloudshine dose rate, 3 h 4 min from start)



- One colored square is appr. 800 m x 800 m
- Map area is appr. 40 km x 40 km
- Olkiluoto in the middle
- City of Rauma marked with grey

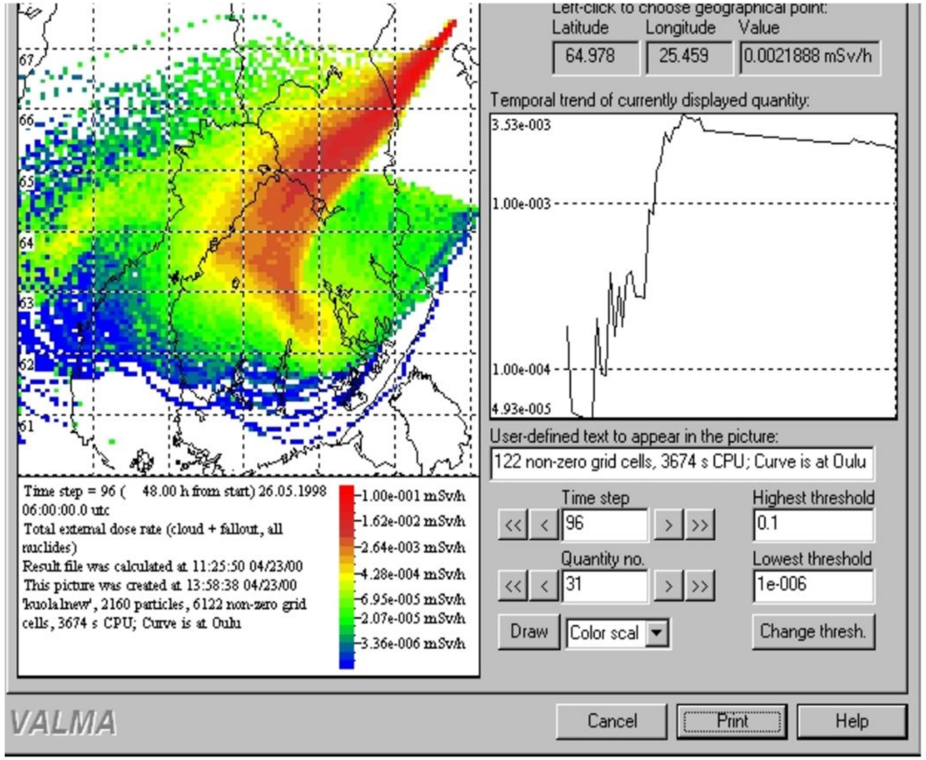
Bigger release VALMA results (cloudshine+groundshine dose rate, 5 h 49 min)



- One colored square is appr. 800 m x 800 m
- Map area is appr. 40 km x 40 km
- Olkiluoto in the middle
- City of Rauma marked with grey

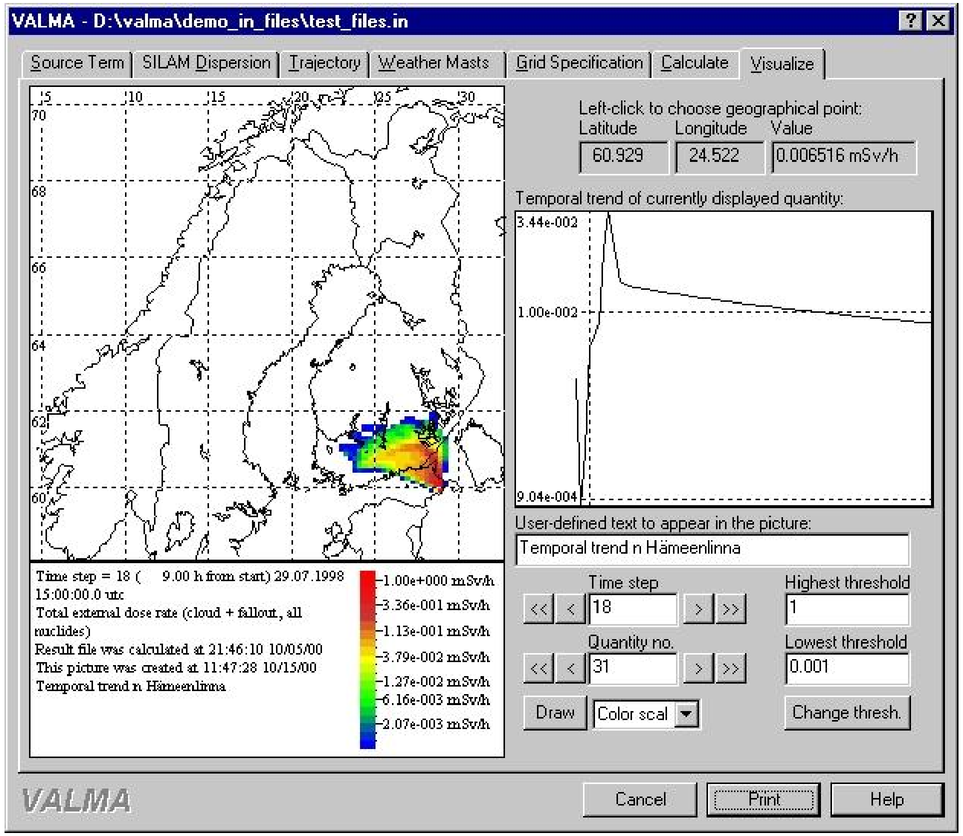
VALMA visualization of SILAM results

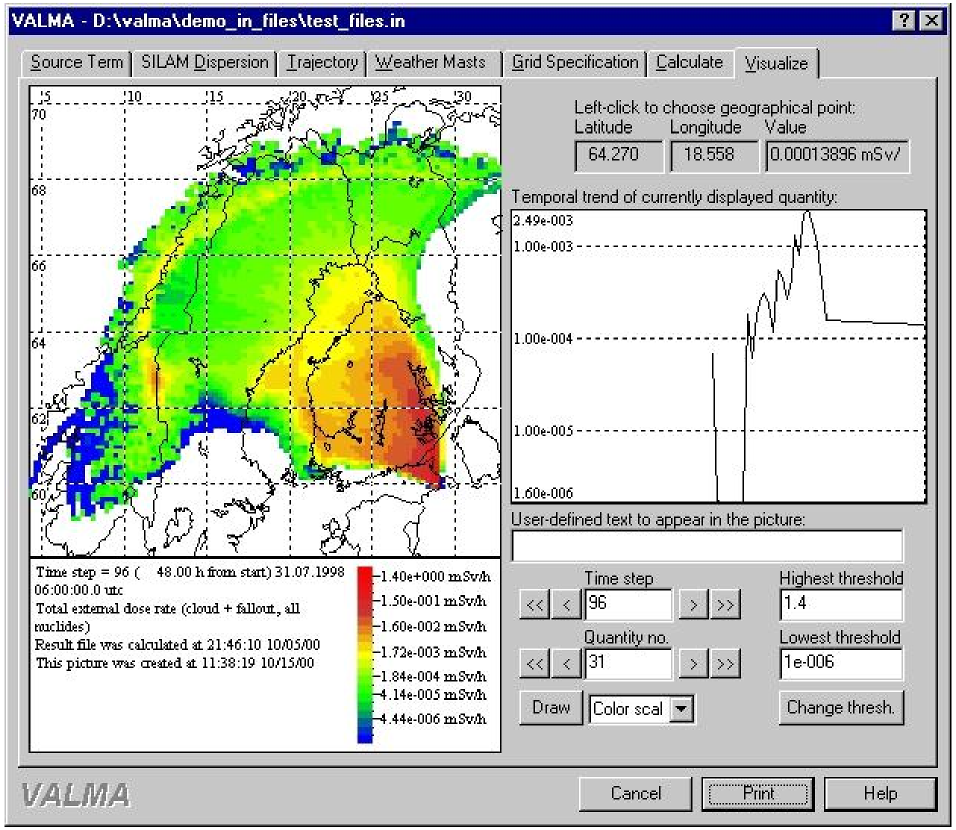
- Example of SILAM dose assessment results
- Visualization by VALMA GUI
- Picture: Hypothetical major release at **Kola** NPP (Russia)
- Shown: External dose rate at +48 h after start of release



Example: Sosnovyy Bor, Russia

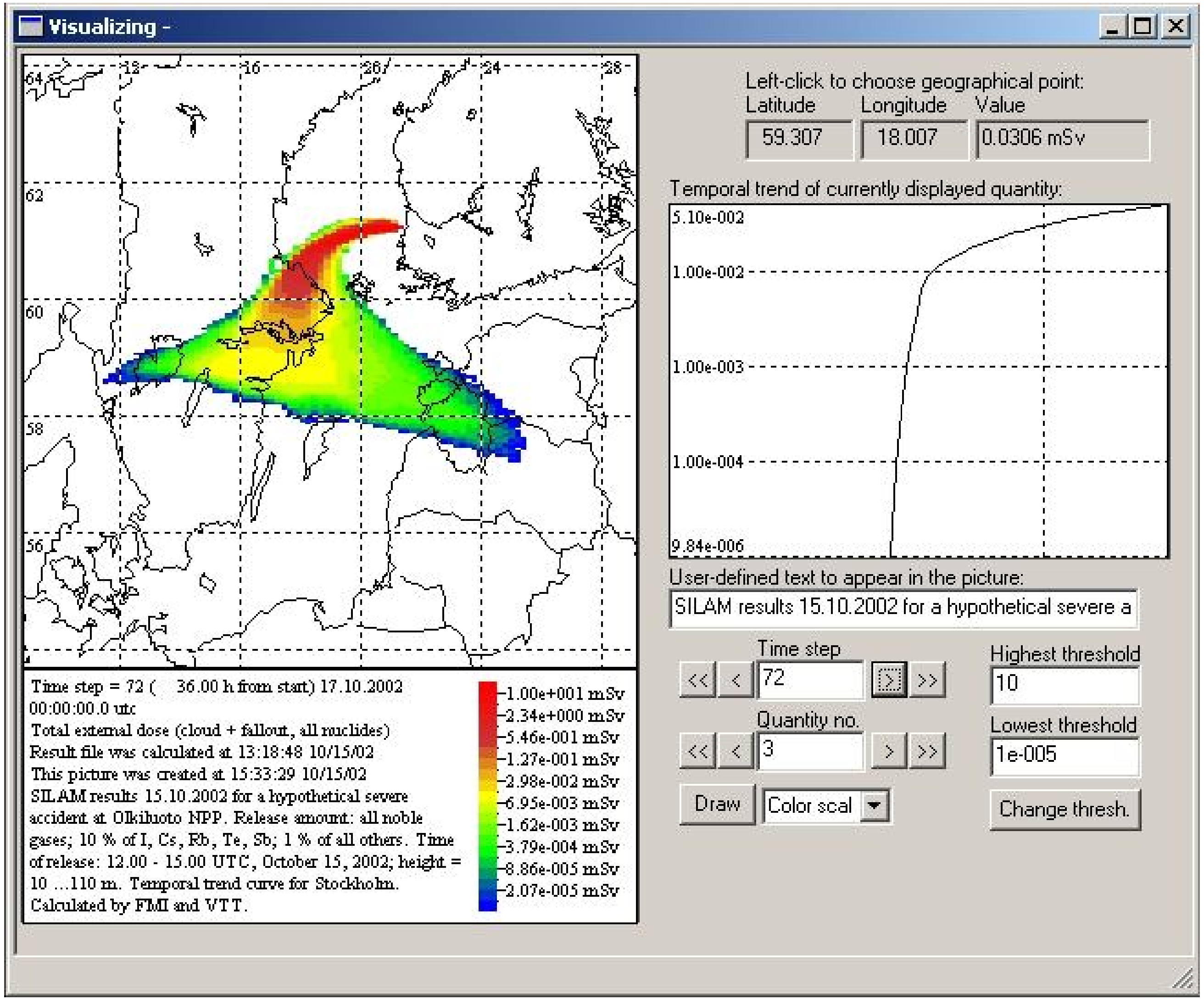
- Total external dose rate mSv/h (cloud and fallout) at 9 h and 48 h after start of release, source is a hypothetical release at Sosnovyy Bor





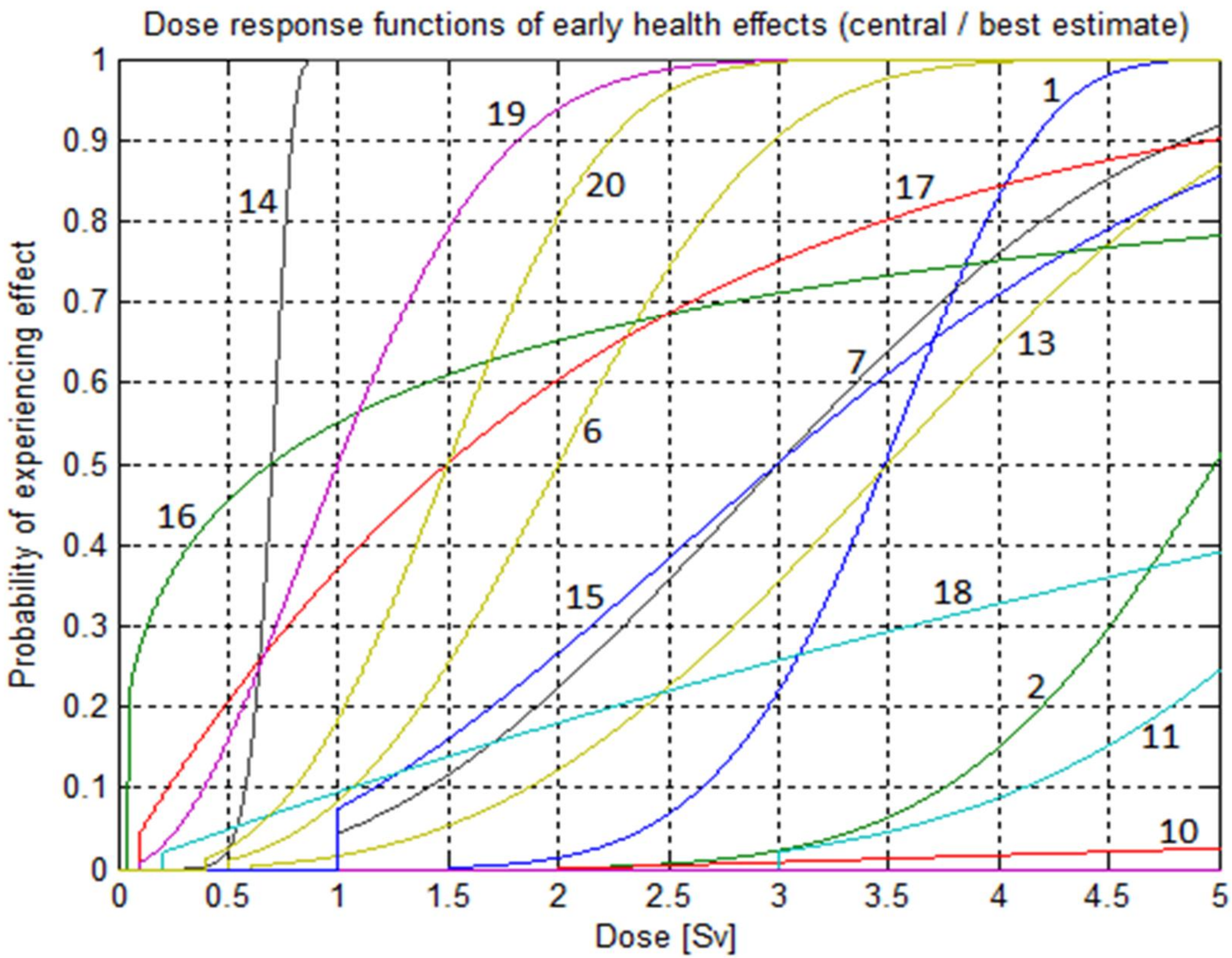
Olkiluoto emergency exercise, October 15, 2002

- The radioactive cloud was transported over the sea towards Stockholm
- This simulation: All noble gases, 10 % of volatiles, 1 % others
- External gamma dose in Stockholm at 36 h is appr. 0.03 mSv



Estimates of health effects with VALMA

- Source of data:
- NUREG / CR 4214, SAND85 7185 (1989-1993)



Health effects available in VALMA: Acute

- 1 = mortality / hematopoietic syndrome / minimal treatment
- 2 = mortality / hematopoietic syndrome / supportive treatment
- 3 = mortality / pulmonary syndrome
- 4 = mortality / gastrointestinal syndrome
- 5 = pulmonary morbidity
- 6 = prodromal syndrome / vomiting
- 7 = prodromal syndrome / diarrhea
- 8 = thyroiditis
- 9 = hypothyroidism / internal exposure to I-131
- 10 = hypothyroidism / all other exposures
- 11 = erythema
- 12 = transepidermal injury
- 13 = reproductive effects / ovulation suppression
- 14 = reproductive effects / suppression of sperm count
- 15 = cataracts
- 16 = in utero / microencephaly / 0 - 17 weeks
- 17 = in utero / severe mental retardation / 8 - 15 weeks
- 18 = in utero / severe mental retardation / 16 - 25 weeks
- 19 = in utero / death of embryo or fetus / 0 - 18 days
- 20 = in utero / death of embryo or fetus / 18 - 150 days

Recent years' work in SAFIR research program

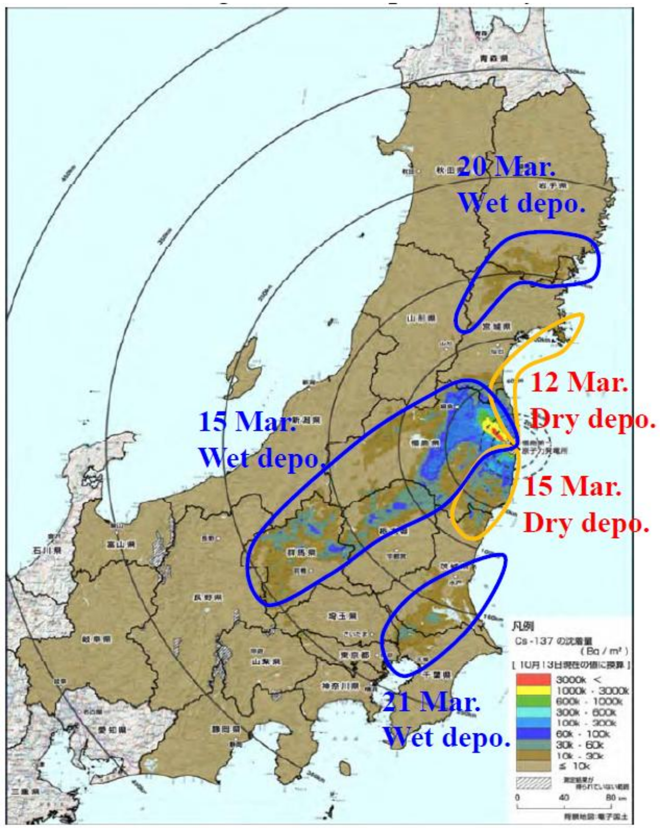
- 01377-13: Fukushima dispersion and doses with ROSA and VALMA
- 00432-15: Dose probability distributions up to 300 km (EPD, ICPD)
- 00589-16: VALMA-calculated probability distributions with 1 a SILAM data
- 00695-17: Assessment of ingestion doses with VALMA
- 00651-18: Off-site radiological consequences from an SMR unit
- 00885-18: Estimates of health effects with VALMA
- 06998-18: EPZ of SMRs by plant suppliers vs. regulatory bodies
- 00136-19: Code-to-code comparisons of ARANO, VALMA and MACCS

- Work going on in 2018-2020:
  - IAEA CRP I31029: Methodology for EPZ assessment of SMRs

- (The codes refer to VTT publications, e.g. VTT-R-01377-13)

NWP data interpolated for Fukushima by FMI (2012)

- Interpolated from NWP fields for the location 141 E, 37.4 N
- Time period 10.3.2011 klo 0:00 – 9.5.2011 klo 23:00
- Data is available at 1 h intervals
- Available quantities:
  - Wind speed (heights 20 m and 100 m)
  - Spread direction (heights 20 m and 100 m)
  - Intensity of rain
  - Cloud coverage
  - Stability class (Pasquill)
- Changing weather conditions, but only at the source point (no CFD-like 3D flow field as function of time)



Cs-137 deposition (Nagai et al. 2012)

Fukushima: VALMA vs. measurements

VALMA result	Monitoring result	Nuclide and date	Monitoring location / region	Reference for monitoring results
Concentrations				
Figure 27 (left)	Figure 16	I-131 / March 12	Fukushima region	Nagai et al. (2012)
Figure 27 (right)				
Figure 28 (left)		I-131 / March 13		
Figure 28 (right)	Figure 10	I -131 / March 15	Tokai-mura	Chino et al. (2011)
Figure 29 (left)		I-131 / March 16		
Figure 29 (right)	-	I-131 / March 20	-	-
Figure 30	Figure 8	Cs-137 / March 15	Tokai-mura	Stohl et al. (2012)
Depositions				
Figure 31 (left)	Figure 18	Cs-137 / March 13	Northern Honshu	Nagai et al. (2012)
Figure 31 (right)		Cs-137 / March 16		
Figure 32		Cs-137 / March 20		
Dose rates				
Figure 33 (left)	Figure 19	March 15	Fukushima-Ibaraki prefectures	Nagai et al. (2012)
Figure 33 (right)		March 16		
Figure 34 (left)		March 16		
Figure 34 (right)		March 12 – 20		

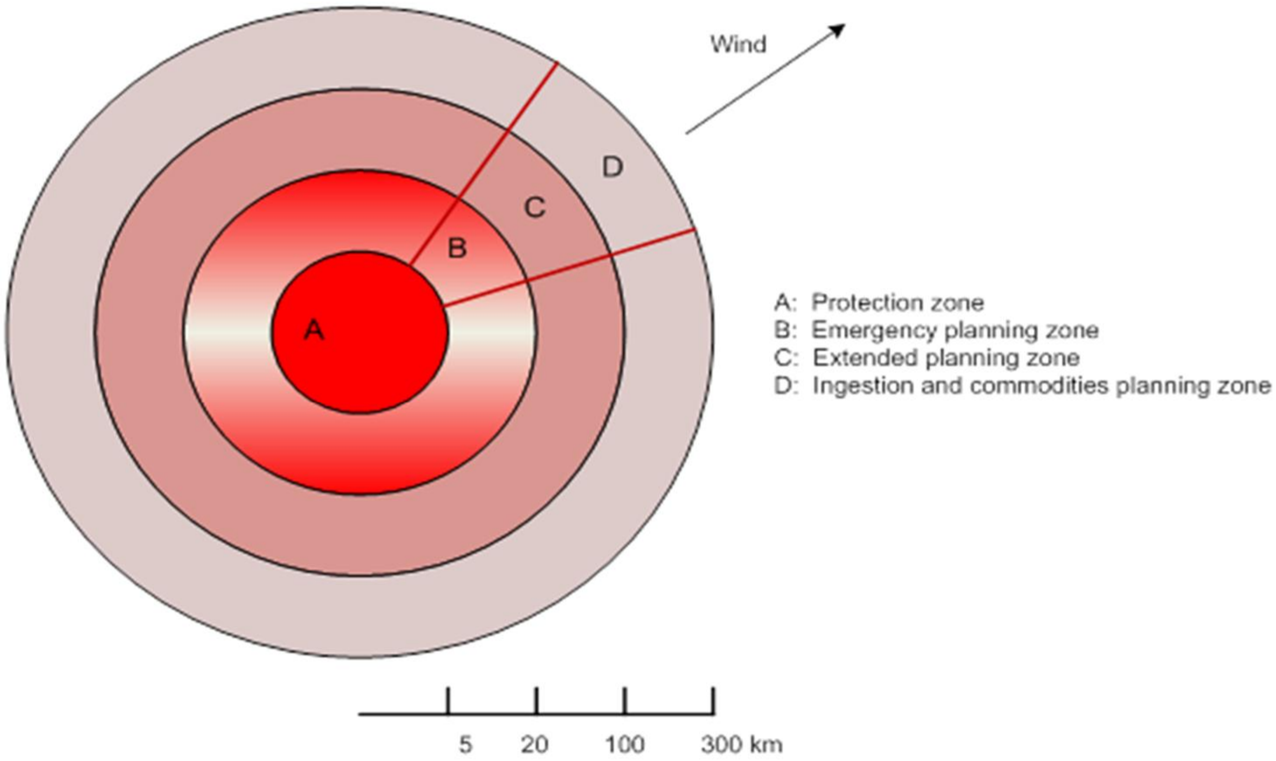
Probability distributions to 300 km (EPD, ICPD)

- IAEA GSR Part 7, affecting European regulations, and Finland
- EPD = extended planning distance (e.g. 100 km)
- ICPD = ingestion and commodities planning distance (e.g. 300 km)

After Fukushima, a new question: ranges > 20 km & frequency distributions of the dose ?

- Also STUK had some new interest in farther distances
- Longer-lasting releases (cf. Chernobyl, Fukushima)
- Better preparedness for dose rates & concentrations farther away from NPP, resulting from atmospheric release of a severe accident
- Realistically calculated <u>dose frequency distributions</u> at certain distances > 20 km, possibly nuclide-per-nuclide
- Difficulty: changing weather conditions, as a 3D field and function of time; can be input from an NWP model
- Complicated models need a lot of CPU time per case
- Other option: choose some representative weather situations; or resort to very conservative methods
- Work in COOLOCE-E in 2014: <u>Review of current tools & feasibility study of producing long-range CCDFs</u>

Zones A & B are used in present planning; C & D are based on new IAEA recommendations



- A: Precautionary action zone PAZ, 5 km
- B: urgent protective actions planning zone UPZ, 20 km
- C: Extended planning zone (EPZ), 100 km
- D: Ingestion and commodities planning zone (ICPZ), 300 km

Emergency preparedness zones around a nuclear power plant (not in scale)

What countermeasures may be relevant outside 20 km ?

- New IAEA and WENRA recommendations call for preparedness for radiological emergency even up to 300 km distance

Radioactive source terms considered

- Case 1: Noble gases 1%, I-131 1000 TBq, Cs-137 100 TBq (Severe accident release)
- Case 2: Noble gases 20%, iodine + caesium 2%
- Case 3: Noble gases 100%, iodine + caesium 20% (No containment)
- Starting height:
  - 80…120 m (stack)
  - 0…200 m, CPU-intensive
- Release timing:
  - Starts 4 h after SCRAM
  - Continues 3 hours

Nuclide	OL3 inventory [Bq]	Release [Bq]		
Noble gases		**Case 1**	**Case 2**	**Case 3**
Kr-85	5.7E+16	5.7E+14	1.1E+16	5.7E+16
Kr-85M	1.3E+18	1.3E+16	2.6E+17	1.3E+18
Kr-87	2.5E+18	2.5E+16	5.0E+17	2.5E+18
Kr-88	3.5E+18	3.5E+16	7.0E+17	3.5E+18
Xe-133	9.7E+18	9.7E+16	1.9E+18	9.7E+18
Xe-133M	3.1E+17	3.1E+15	6.2E+16	3.1E+17
Xe-135	3.0E+18	3.0E+16	6.0E+17	3.0E+18
Xe-135M	2.1E+18	2.1E+16	4.2E+17	2.1E+18
Xe-138	8.6E+18	8.6E+16	1.7E+18	8.6E+18
Iodine				
I-131	4.8E+18	1.0E+15	9.6E+16	9.6E+17
I-132	7.0E+18	1.5E+15	1.4E+17	1.4E+18
I-133	1.0E+19	2.1E+15	2.0E+17	2.0E+18
I-134	1.1E+19	2.3E+15	2.2E+17	2.2E+18
I-135	9.5E+18	2.0E+15	1.9E+17	1.9E+18
Cesium + rubidium				
Cs-134	9.3E+17	1.5E+14	1.9E+16	1.9E+17
Cs-136	2.3E+17	3.6E+13	4.6E+15	4.6E+16
Cs-137	6.4E+17	1.0E+14	1.3E+16	1.3E+17
Cs-138	9.3E+18	1.5E+15	1.9E+17	1.9E+18
Rb-88	3.6E+18	5.6E+14	7.2E+16	7.2E+17
Rb-89	4.7E+18	7.3E+14	9.4E+16	9.4E+17

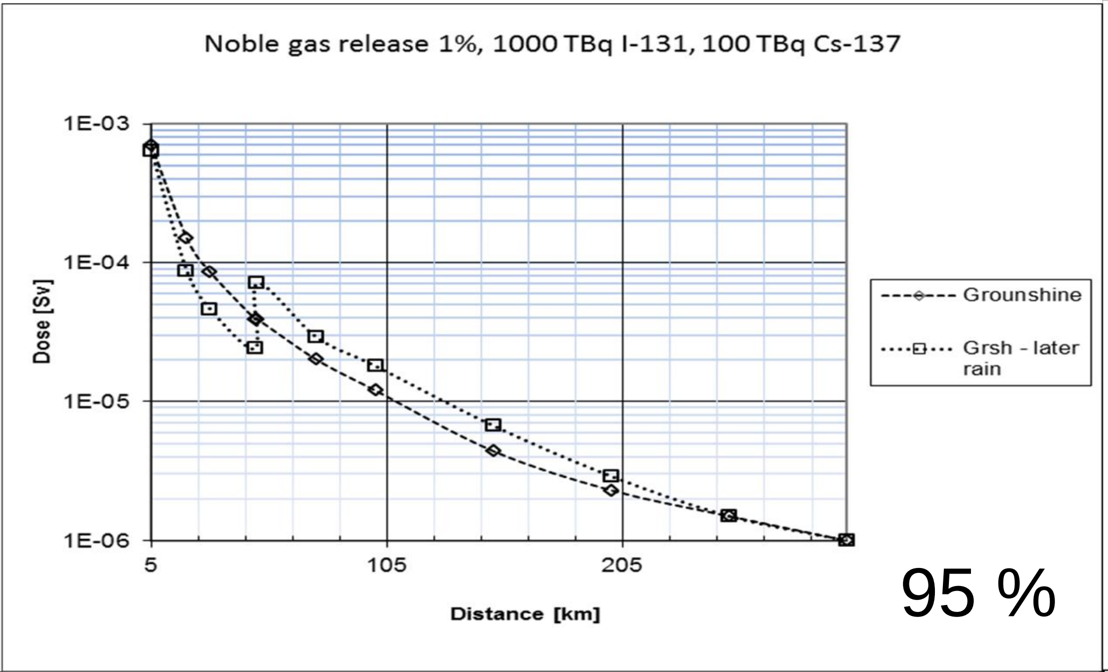
Calculations with ARANO, 5…20…300 km

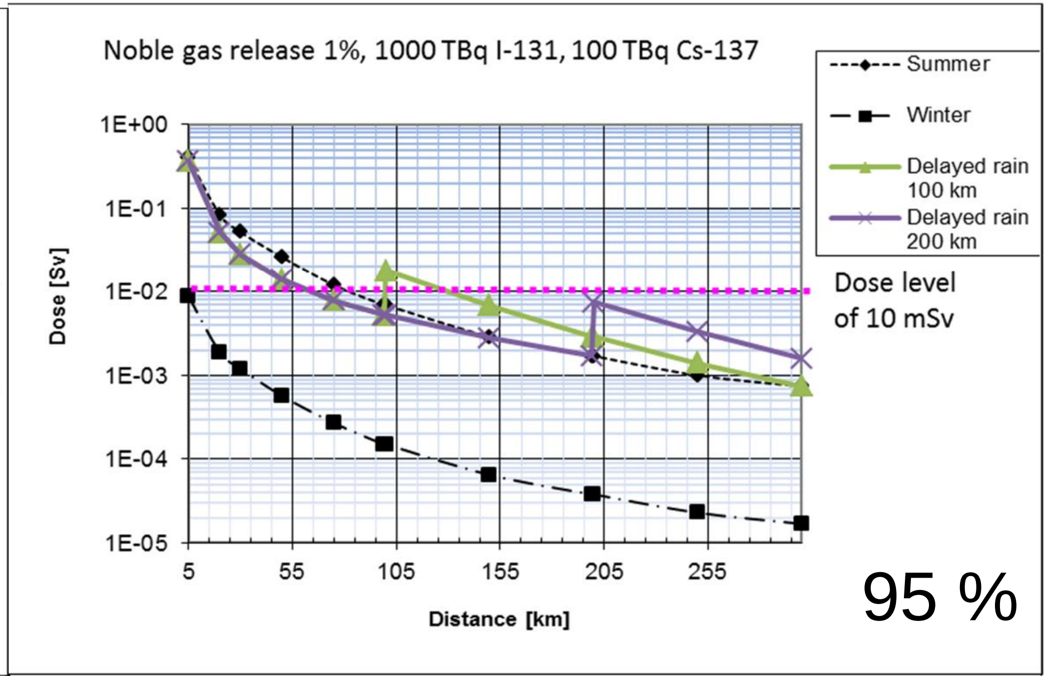
Weather data: Olkiluoto 2009…2013
Source term specified by STUK:

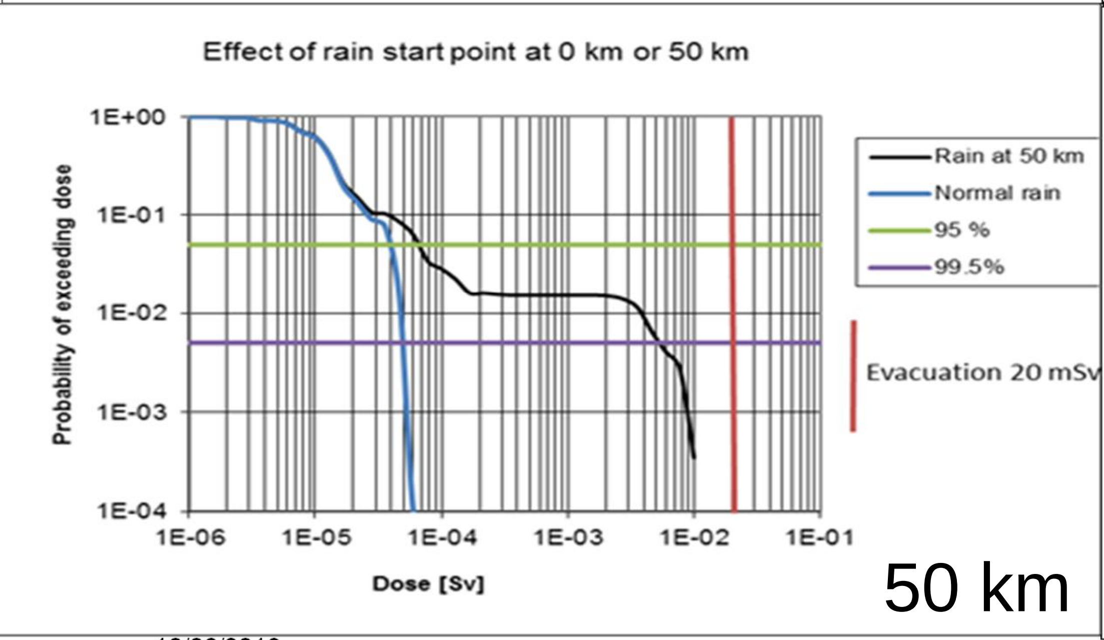
- Olkiluoto-3 inventory
- Severe accident, 3 nuclide groups
- Release magnitude 1, 10 ,100 * 100 TBq
- Decay time 4 h after SCRAM, release duration 3 h

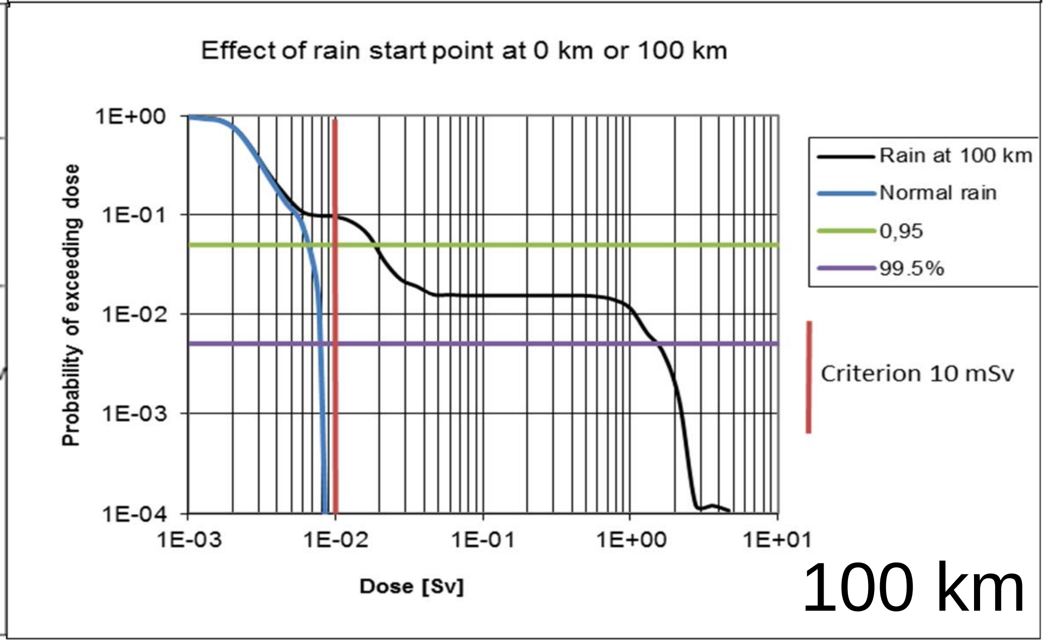
- Comparison with VALMA
- More extensive ARANO / VALMA calculations in 2015
- Availability of better weather data

Groundshine / ingestion; top: 95 % fractile, bottom: CCDF









Groundshine

Ingestion

VALMA-calculated distributions with SILAM data

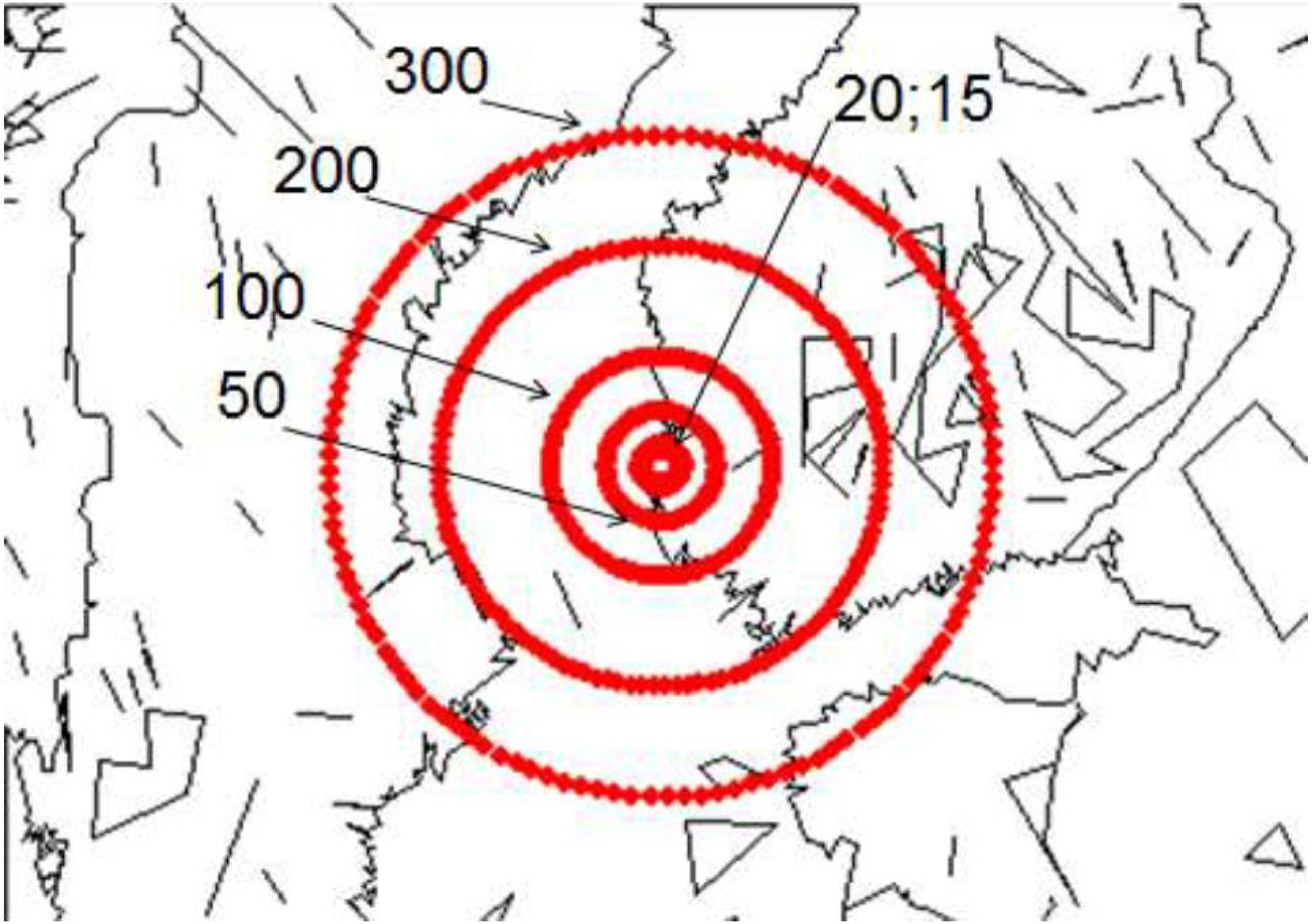
- ARANO is basically not suitable at longer distances (Gaussian, max 20 km?)
- VALMA can use SILAM trajectories, but needs much longer calculation times
- Can we (practically) produce CCDFs from several years of SILAM-based weather data (i.e. n x 8760 cases, for example)?

- The result of ARANO vs. VALMA comparison:
  - One case may be totally different because of Gaussian vs. SILAM
  - However, for a large number of cases, these deviations seem to somewhat cancel out, leading to quite similar CCDFs

SILAM dispersion data for 2012 (FMI), used in VALMA dose calculations

- Calculated by Julius Vira (FMI), October 2015
- 1 Jan … 31 Dec 2012
- For Olkiluoto NPP site
- Air parcel trajectories (i.e. massless particles)
- No gravitational settling, even for aerosol form particles
- ECMWF (European Centre for Medium-range Weather Forecasts) numerical weather prediction model
- Horizontal resolution of NWP data was 16 km x 16 km
- 20 trajectories every 12 min (= 100 / hour), appr. 9 GB
- A total of 878400 trajectories, followed for max. 96 h each
- Release height 0…200 m
- In VALMA, it was specified: 4 h cooling time, 3 h release duration

Considered locations around Olkiluoto 3



Picture from VALMA GUI

Figure 3.1. Graph of the calculation distances around the nuclear power plant. Ring 1 corresponds to 15 km,ring 2 to 20 km, ring 3 to 50 km, etc.

Total dose cloudshine + groundshine + inhalation [mSv] at the 6 distances, 95% percentile, case 3. Time integral of 1 year.

Distance [km]	**VALMA, Mean**	**VALMA, Median**	**VALMA, Maximum**	**ARANO (mean)**
15	4550	4770	9770	3000
20	3180	3300	6850	2000
50	965	969	2130	550
100	439	400	1020	150
200	180	150	435	40
300	118	94.3	287	20

Assessment of ingestion doses with VALMA

- Based on activity deposited on the ground surface
- VTT models for ingestion doses: AGRID (simpler), DETRA
- In this work, the objective was to include ’on-the-fly’ (as part of the dispersion and dose assessment) assessment of ingestion doses in VALMA
- Finnish agricultural products, winter season / growing season
- Coefficients as Sv / (Bq/m2) were based on the AGRID model of VTT

AGRID model description 1/2

- VTT-made nutrition dose code, 'Agricultural Doses'
- Originally inspired by FOOD-MARC model of the British NRPB
- 3 vegetable dose pathways (green vegetables, grain, roots)
- 2 animal dose pathways (cow milk, cow meat)
  - Calculation methods differ for vegetables and animals
- Agrid accounts for Nordic seasons in agriculture
- For the 3 vegetable dose pathways:
  - Dose due to root uptake is present for all time points (of receiving deposition) during the year
    - The next 30 years' root uptake is taken into account
  - During the growing season (60 d), also direct deposition on plants causes doses to consumers (intake of deposition year)
    - Time delays (rad. decay) before harvesting / consumption

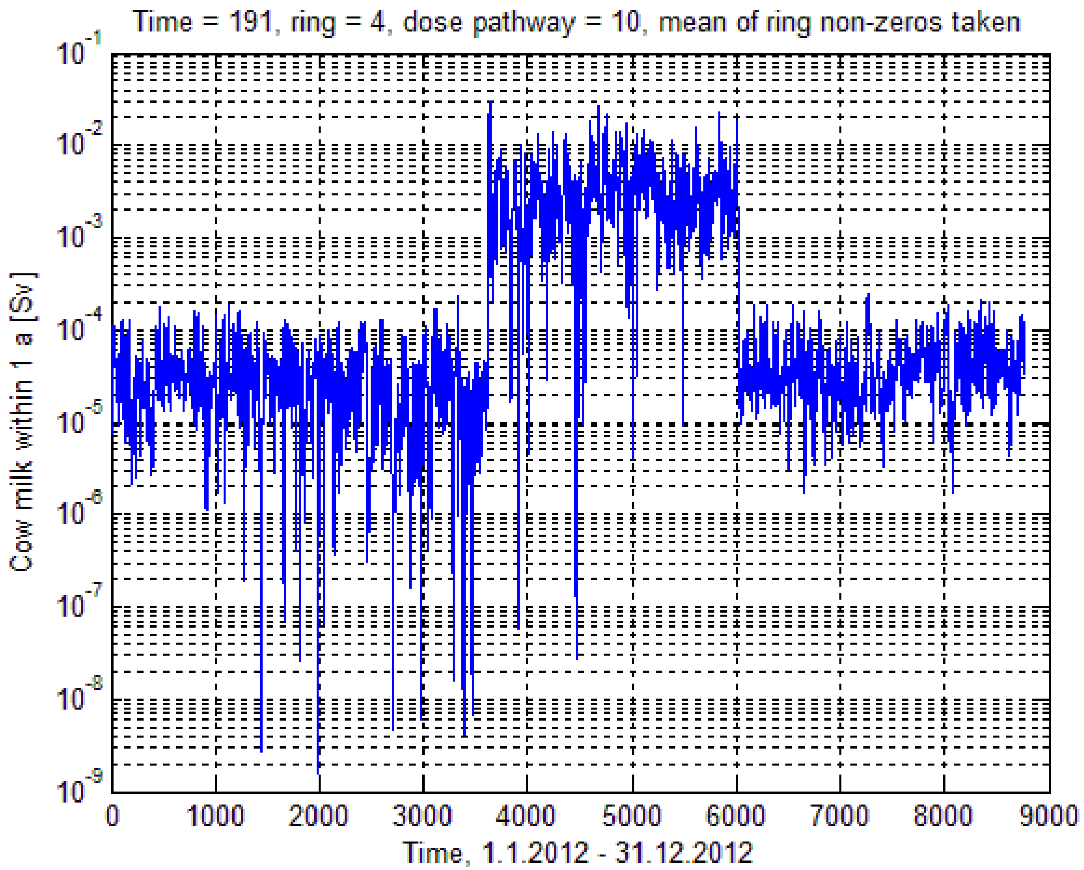
AGRID model description 2/2

- For the 2 animal dose pathways:
  - Pasture – cow – milk – man
    - Effective whole body dose & thyroid dose via milk
  - Pasture – cattle – meat – man
    - Effective whole body dose
- Dose is the sum of 3 time periods:
  - 1st year, pasture season (100 d) or winter time
  - Years 2-3
  - Years 4-30, ground assumed to be ploughed after 3 years

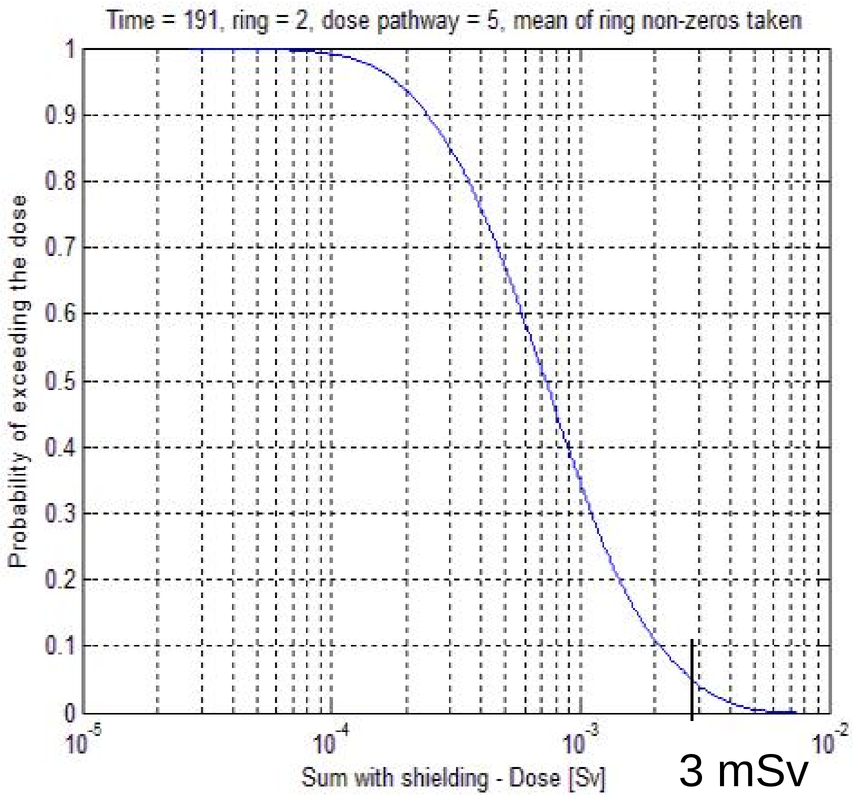
Example of dose coefficients table (Ingestion of milk or meat,1 year)

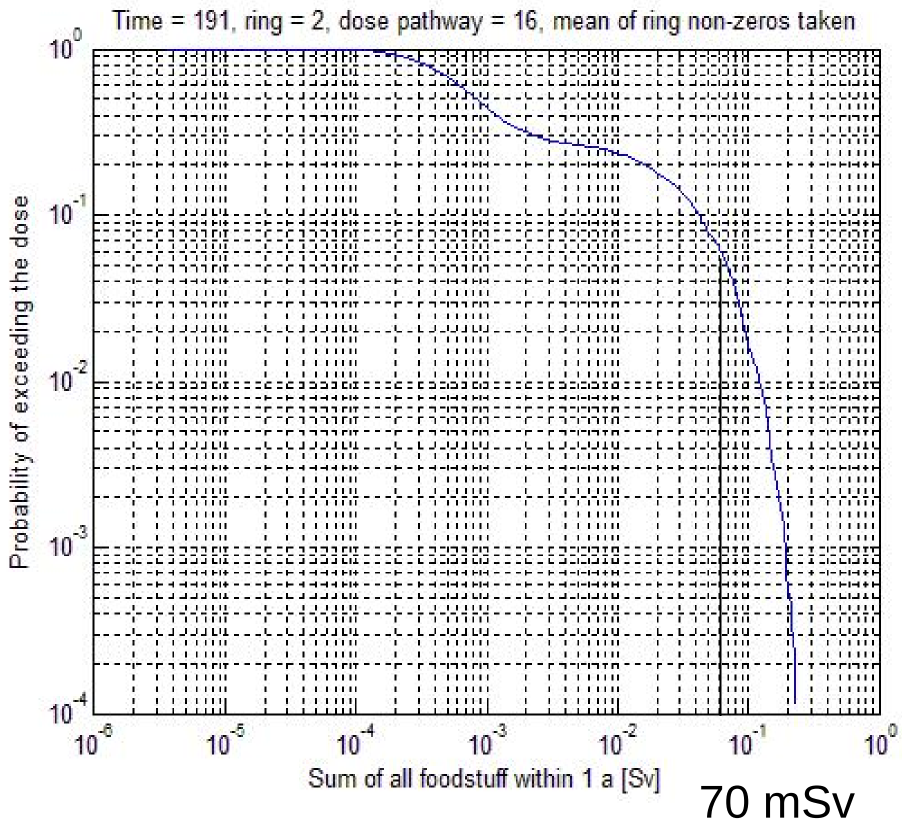
		Summer		Winter	
		Milk	Meat	Milk	Meat
1	KR85	0.00E+00	0.00E+00	0.00E+00	0.00E+00
2	KR85M	0.00E+00	0.00E+00	0.00E+00	0.00E+00
3	KR87	0.00E+00	0.00E+00	0.00E+00	0.00E+00
4	KR88	0.00E+00	0.00E+00	0.00E+00	0.00E+00
5	SR89	3.55E-12	7.58E-13	7.15E-14	2.16E-14
6	SR90	2.96E-10	8.65E-11	6.72E-11	2.05E-11
7	SR91	0.00E+00	0.00E+00	0.00E+00	0.00E+00
8	Y90	0.00E+00	0.00E+00	0.00E+00	0.00E+00
9	Y91	7.37E-14	8.96E-14	1.93E-16	2.00E-14
10	ZR95	0.00E+00	0.00E+00	0.00E+00	0.00E+00
11	ZR97	0.00E+00	0.00E+00	0.00E+00	0.00E+00
12	NB95	1.26E-11	7.61E-14	1.69E-14	1.66E-15
13	MO99	1.15E-13	5.20E-14	2.02E-27	1.56E-26
14	TC99M	0.00E+00	0.00E+00	0.00E+00	0.00E+00
15	RU103	4.00E-16	8.67E-14	1.90E-18	8.08E-15
16	RU105	0.00E+00	0.00E+00	0.00E+00	0.00E+00
17	RU106	1.52E-14	1.20E-11	6.74E-16	2.76E-12
18	RH105	0.00E+00	0.00E+00	0.00E+00	0.00E+00
19	TE129	0.00E+00	0.00E+00	0.00E+00	0.00E+00
20	TE129M	8.00E-13	1.22E-11	3.62E-14	8.89E-13
21	TE131M	0.00E+00	0.00E+00	0.00E+00	0.00E+00
22	TE132	6.35E-14	1.88E-13	2.91E-25	5.86E-24
23	I131	5.08E-11	9.76E-12	2.27E-18	1.46E-18
24	MI131	0.00E+00	0.00E+00	0.00E+00	0.00E+00
25	I132	1.01E-24	2.70E-30	0.00E+00	0.00E+00
26	I133	1.43E-13	1.99E-15	0.00E+00	0.00E+00
27	I134	0.00E+00	0.00E+00	0.00E+00	0.00E+00
28	I135	3.19E-17	2.64E-20	0.00E+00	0.00E+00
29	MI135	0.00E+00	0.00E+00	0.00E+00	0.00E+00

Dose from the locally produced milk (consumption of first year), CASA1 source term, mean non-zero value at the distance of 100 km; as a function of release start time.



Example. CCDF for total mean dose (cloud + fallout + inhalation, left; vs. ingestion, right), 20 km, 1 year, release 'CASA1'





Example. Statistics of VALMA dose results (ingestion pathways) with release 'CASA1'

1. running line number (1-180)
2. distance from Olkiluoto NPP (15 / 20 / 50 / 100 / 200 / 300 km)
3. ingestion dose pathway (1 = green vegetables, 2 = grain, 3 = root vegetables, 4 = milk, 5 = meat, 6 = sum (1+2+3+4+5)
4. time frame within which the contaminated fields are used
5. statistic describing one dispersion case at the distance: mean, median, or maximum of affected receptor points
6. mean dose of the dispersion cases of year 2012
7. median dose of the dispersion cases of year 2012
8. the '95 % dose', i.e. the probability of exceeding it is 5 %
9. the '99.5 % dose', i.e. the probability of exceeding it is 0.5 %
10. maximum dose of the dispersion cases of year 2012

1	2	3	4	5	6	7	8	9	10
1	15km	1	1a	mean	7.98e-04	5.87e-06	5.44e-03	1.44e-02	3.05e-02
2	15km	1	1a	med	7.94e-04	5.85e-06	5.40e-03	1.49e-02	4.34e-02
3	15km	1	1a	max	1.70e-03	1.22e-05	1.19e-02	2.92e-02	4.90e-02
4	15km	1	3a	mean	8.09e-04	1.45e-05	5.48e-03	1.44e-02	3.06e-02
5	15km	1	3a	med	8.05e-04	1.43e-05	5.43e-03	1.50e-02	4.36e-02
6	15km	1	3a	max	1.73e-03	3.01e-05	1.20e-02	2.93e-02	4.92e-02
7	15km	1	30a	mean	8.57e-04	5.53e-05	5.56e-03	1.46e-02	3.11e-02
8	15km	1	30a	med	8.53e-04	5.44e-05	5.50e-03	1.52e-02	4.42e-02
9	15km	1	30a	max	1.83e-03	1.15e-04	1.22e-02	2.98e-02	4.99e-02

Off-site consequences from a SMR unit - Public-funded reasearch by VTT in 2017 (a small project)

- SMR = small modular reactor
- In Finland, some interest expressed by the utility Fortum
- Also some cities (Helsinki, Espoo, Kirkkonummi): heating w/o CO_2
  - Easier funding than big (typically > 1 GW) NPPs
  - Enhanced safety features, including passive systems
  - Enhanced barriers for radionuclide releases
- Sites near cities / industry (district / process heat, desalination)
- Can the emergency planning zones be reduced?
- Not yet a specific (SMR) graded approach for licensing in Finland
- We proceeded with approximate core inventory & expert judgement of fractions released into the atmosphere

SMR radiological consequences: The (ideal) probabilistic procedure to determine right-sized EPR zones

- Perform the complete plant-specific PRA, including also deterministic investigations of phenomena:
- Level 1(core damage frequencies):
  - Transient scenarios leading to core damage
- Level 2 (atmospheric releases with their frequencies):
  - Inventory, release from fuel, release through containment barriers
- Level 3: Off-site doses with their frequencies:
  - Use real site-specific weather data of several years
- Accounting for collocation (multiple units) – how probable?
- Emergency Preparedness Zones are based on expected doses & frequencies, dose limits for countermeasures, and the practical possibility to perform the countermeasures

Ideal basic steps in EPR zone sizing (1/2)

- Core radioactive inventory should be calculated or acquired from designer; Origen, Serpent
- Postulated DBA accidents should be listed and described.
- Possibility of a severe accident (with core melt) should also be considered (however improbable it may be).
- Estimates of the atmospheric release source term
  - Direct information from designer
  - Expert judgement starting from core radioactive inventory
  - Computational assessment using an integral code (e.g. MELCOR)
- Worst case (deterministic) radioactive source term from containment into the atmosphere

Ideal basic steps in EPR zone sizing (2/2)

- Consideration of site-specific conditions (weather, surrounding environment, population)
- Selecting and acquiring representative weather data
- Off-site dispersion and dose assessment (public doses) calculations with the selected code or codes
  - ARANO, VALMA (VTT), MACCS, RASCAL (NRC)
- Picking of relevant dose results:
  - Relevant dose pathways (inhalation, cloudshine, groundshine; bone marrow, lungs)
  - Chosen fractiles (95 % or 99.5 %), i.e. dose level which is exceeded only with low probability
  - Distances from plant representative of possible extent of the EPZ
- Comparison of predicted dose levels with IAEA / STUK criteria for protective measures
- Justified recommendation of EPZ size, based on expectedly needed protective measures

Doses at distances of 1, 2, 3, 5, 8, 12 km -How would EPZ compare with previous figures?

- IAEA GS-G-2.1 (Arrangements for preparedness for a nuclear or radiological emergency) recommends for 160 MWth:
  - PAZ (precautionary action zone) = 0.5 … 3 km
  - UPZ (urgent protective action zone) = 5 … 30 km
- VALMA sum cloud+fallout+inhalation (Sv), median of one case values appearing at the distance, 95 % fractile of year 2012 cases:

	1 km	2 km	3 km	5 km	8 km	12 km
3.5 h	0.0622	0.0290	0.0172	0.0094	0.0052	0.0029
1 d	0.0619	0.0290	0.0171	0.0095	0.0052	0.0029
2 d	0.0622	0.0292	0.0171	0.0095	0.0052	0.0029
1 week	0.0631	0.0296	0.0174	0.0097	0.0053	0.0030
1 month	0.0652	0.0306	0.0180	0.0100	0.0055	0.0031
1 year	0.0704	0.0331	0.0194	0.0108	0.0060	0.0033

Doses at distances of 1, 2, 3, 5, 8, 12 km
-Time / distance tables with other choices

- VALMA sum cloud+fallout+inhalation (Sv), maximum of one case values appearing at the distance, 99.5 % fractile of year 2012 cases:

	1 km	2 km	3 km	5 km	8 km	12 km
3.5 h	0.3350	0.1480	0.0893	0.0421	0.0205	0.0109
1 d	0.3370	0.1480	0.0898	0.0423	0.0206	0.0109
2 d	0.3390	0.1490	0.0903	0.0426	0.0207	0.0110
1 week	0.3440	0.1510	0.0915	0.0431	0.0210	0.0111
1 month	0.3550	0.1560	0.0945	0.0446	0.0217	0.0115
1 year	0.3830	0.1690	0.1020	0.0481	0.0234	0.0124

Importance of near-field dispersion effects for SMR (VTT-R-06998-18) >> CFD approach?

- Many SMR designs locate the reactor underground, or at least the size of the building is smaller than for large NPPs. Possibly the initial heat content is smaller. These factors will make the effective release height smaller, meaning a more concentrated radioactive cloud in the nearby areas. Furthermore, the possible offsite adverse effects are inherently located more pronouncedly in the nearby areas only, because of the small source. Potential siting near population centers makes it very important to study those near-field effects in great detail.
-
- Building wake: Turbulent eddies around buildings provide more initial spread.
- Stack-tip downwash (high-rise structures causing downwards transfer of activity concentrations)
- Cloud rise (plume rise): Initial upward momentum and heat content make the release rise higher than stack height right at the starting point.
- Near-field dispersion parameters: Weather mast measurements may be more reliable near the source than NWP (numerical weather prediction) model, but more masts than one single would make the data even more reliable and complete.
- Very narrow plume: It takes some time for the release to spread in the lateral and vertical directions, and when e.g. using the Gaussian model, choice of appropriate parameters is very important.
- Urban / industrial terrain: Terrain roughness may decrease wind speeds locally and induce turbulence. Furthermore, spread directions may favor street ‘canyons’ etc.

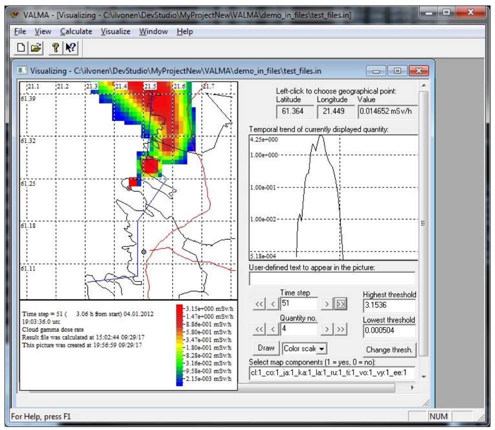
VTT participation in IAEA CRP I31029

Development of Approaches, Methodologies and Criteria for Determining the Technical Basis for Emergency Planning Zone for Small Modular Reactor Deployment

- Formulate criteria for the events and technical aspects to be considered for defining emergency preparedness & response (EPR) arrangements for SMR, focusing on EPZ sizing.
- Develop approaches and methodologies which enable relating safety features of SMRs with the extent of offsite arrangements needed, particularly the size of EPZ
- Provide suitable technical basis, as an input into the development of IAEA technical guidance (EPR series report) on EPR arrangements for SMRs.

Code-to-code comparisons of ARANO, VALMA (VTT codes) and MACCS 3.10.2 (NRC)

- ARANO & MACCS:
  - Offsite dose calculations without countermeasures in a single weather condition as well as with the probabilistic approach employing annual weather data.
  - The principal phenomena included in the codes are atmospheric transport and deposition under prevailing meteorology, short- and long-term mitigation actions and exposure pathways, deterministic and stochastic health effects, and economic costs.
- VALMA is more restricted but with higher-fidelity dispersion:
  - Connection to 3D numerical weather prediction (NWP)
  - Best suitable for distances > 5 km
  - Made originally for emergency preparedness & resp.
  - Protective measures not included in the calculations
  - More CPU time



Comparison of ARANO, MACCS and VALMA

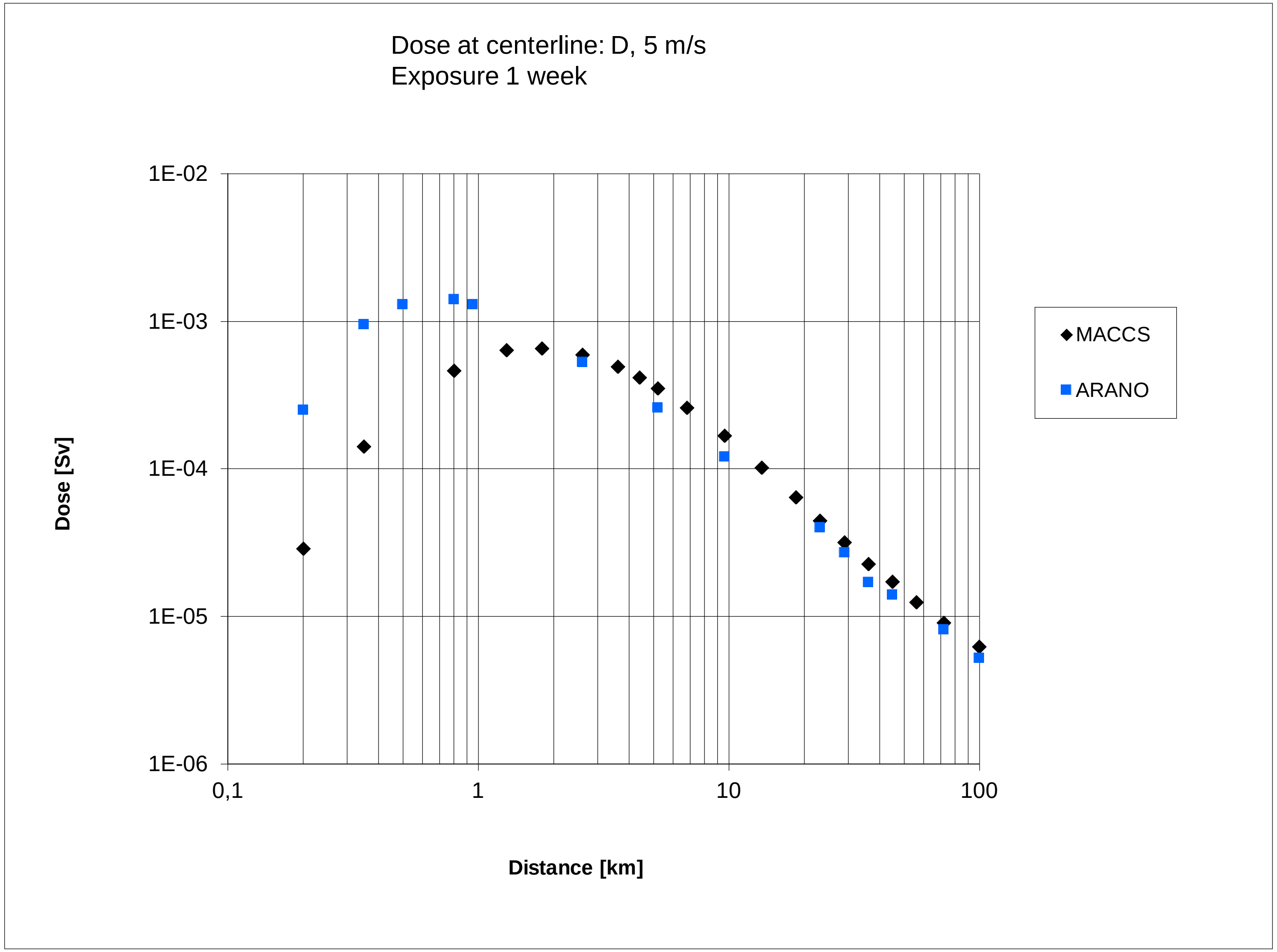
- Note: First ARANO-MACCS comparisons were made in 1982 and 1994
  - OECD/NEA 1994. Probabilistic Accident Consequence Assessment Codes, Second International Comparison, Technical Report EUR 15109, CEC
- VALMA is a VTT-developed in-house code, primarily suited for distances > 5 km, using NWP 3D weather data
- ARANO works well even for near-field (< 500 m)
- Cloudshine from actual shape of the plume
  - Algorithm is based on pre-calculated dose rate files for successive stages of the evolving Kz vertical profile
  - Wind meandering in longer duration releases accounted for

Single weather comparison runs, Non-ingestion exposure pathways

- Cloudshine, groundshine and inhalation. Moreover, resuspension is included in MACCS. Dose is the sum of these components.
- The source term input is: Cs-137 (t_{half} = 30.17 a) 100 TBq, duration of the release 0.5 h, without delay from the shutdown, release altitude 100 m.
- Some weather situations used in single weather cases:

	Stability	Wind (m/s)	Rain (mm/h)	Nuclide (t 1/2)
1, 2	D	5	no rain	Cs-137 (30.17 a)
3	C	5	5	Cs-137
4	F	1	no rain	I-131 (8 d), I-133
5	D	5	0.7	Cs-137

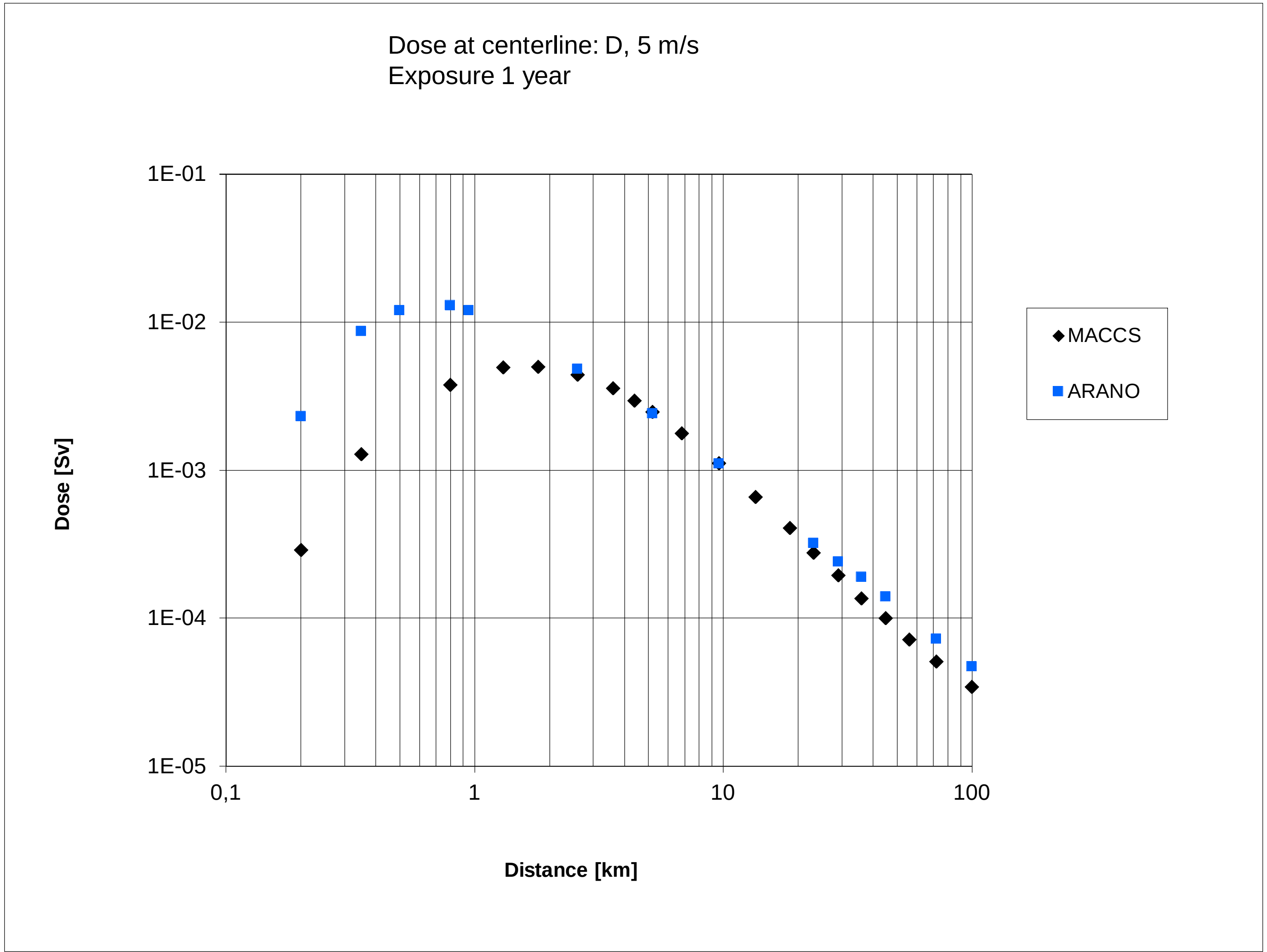
Single weather, Non-ingestion exposure pathways ('1')



- Cs-137, 100 TBq
- Stability D
- 5 m/s
- No rain
- 1 week exp.

- ARANO higher up to 2 km from source
- As much as 10x

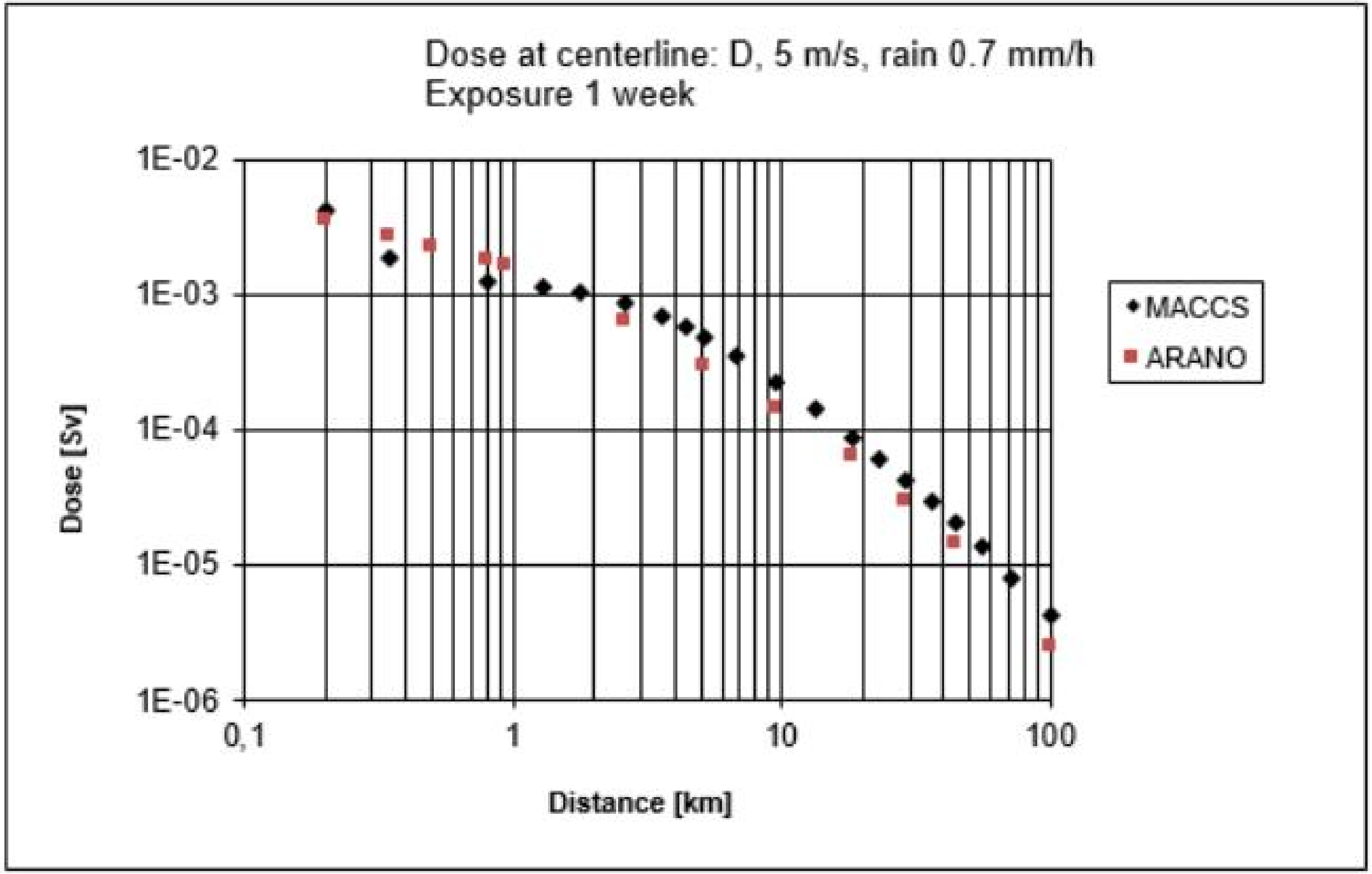
Single weather, Non-ingestion exposure pathways ('2')



- Cs-137, 100 TBq
- Stability D
- 5 m/s
- No rain
- 1 year exp.

- ARANO higher up to 3 km from source (even 10x) and farther than 20 km

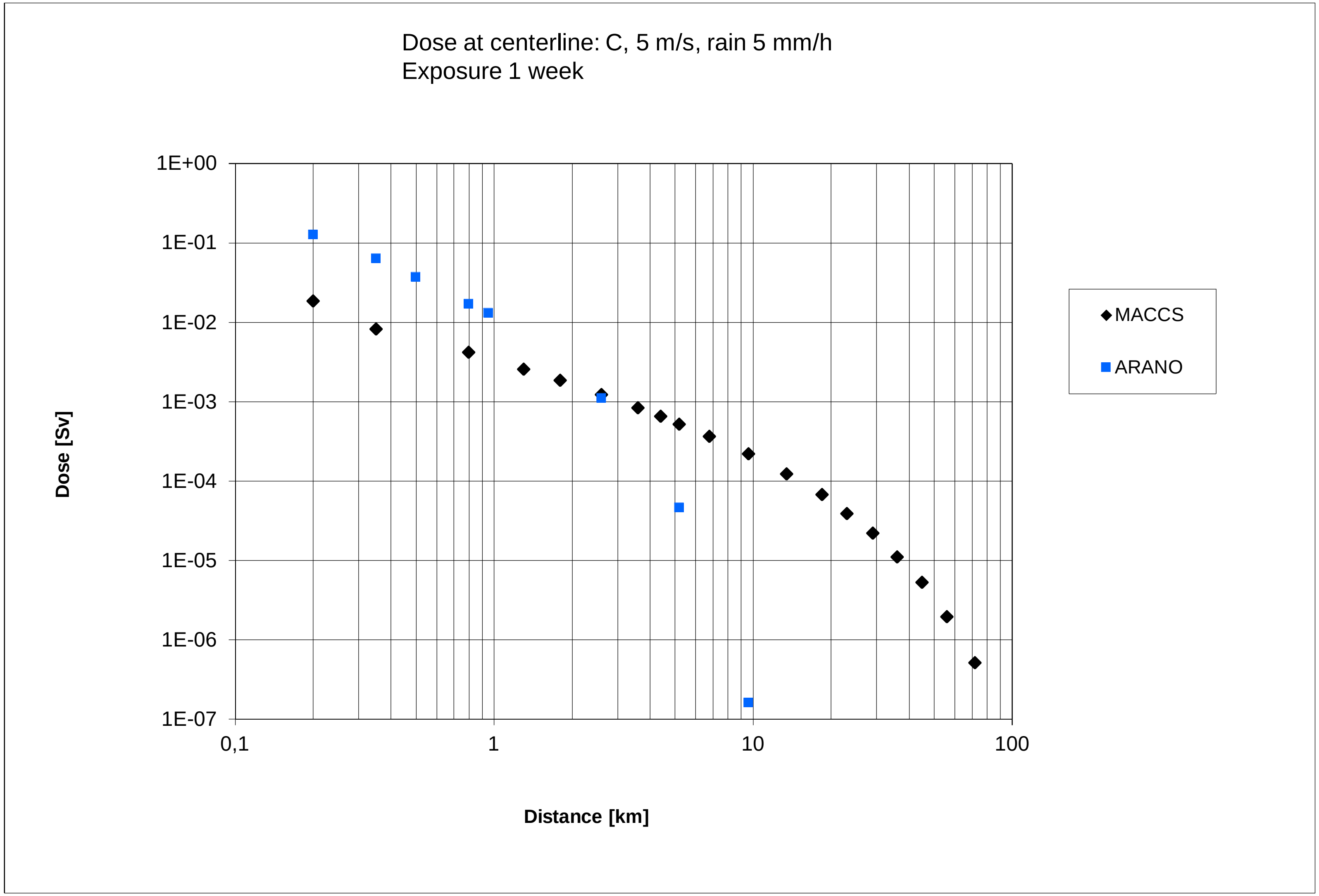
Single weather, Non-ingestion exposure pathways ('5')



- Cs-137, 100 TBq
- Stability D
- 5 m/s
- Rain 0.7 mm/h
- 1 week exp.

- ARANO higher up to 1 km
- No big difference when weak rain

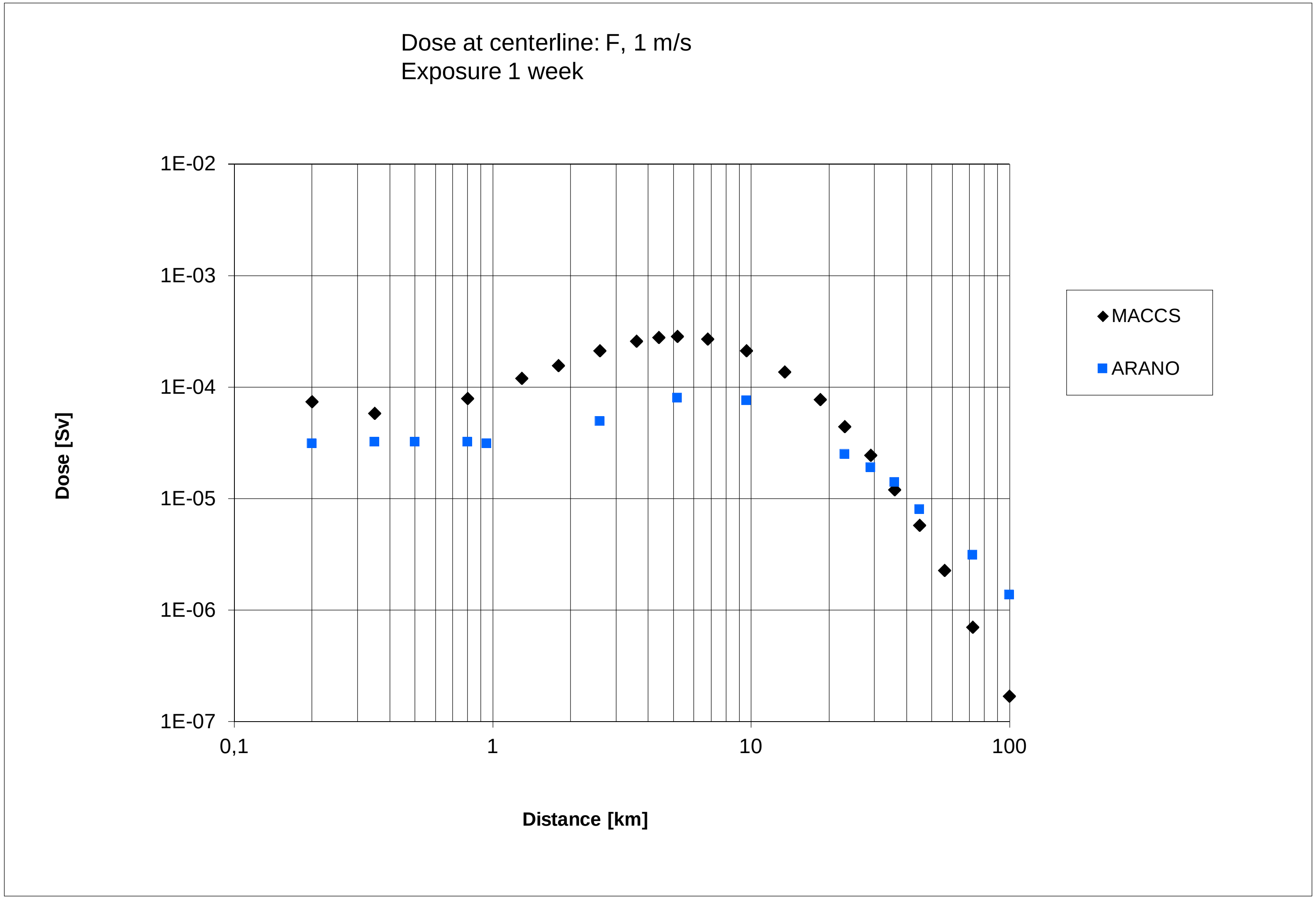
Single weather, Non-ingestion exposure pathways ('3')



- Cs-137
- Stability C
- 5 m/s
- Rain 5 mm/h
- 1 week exp.

- ARANO higher up to 2 km
- After 2 km, heavy rain seems to have scavenged a lot more in ARANO

Single weather, Non-ingestion exposure pathways ('4')



- Iodine
- Stability F
- 1 m/s
- No rain
- 1 week exp.

'BAD'

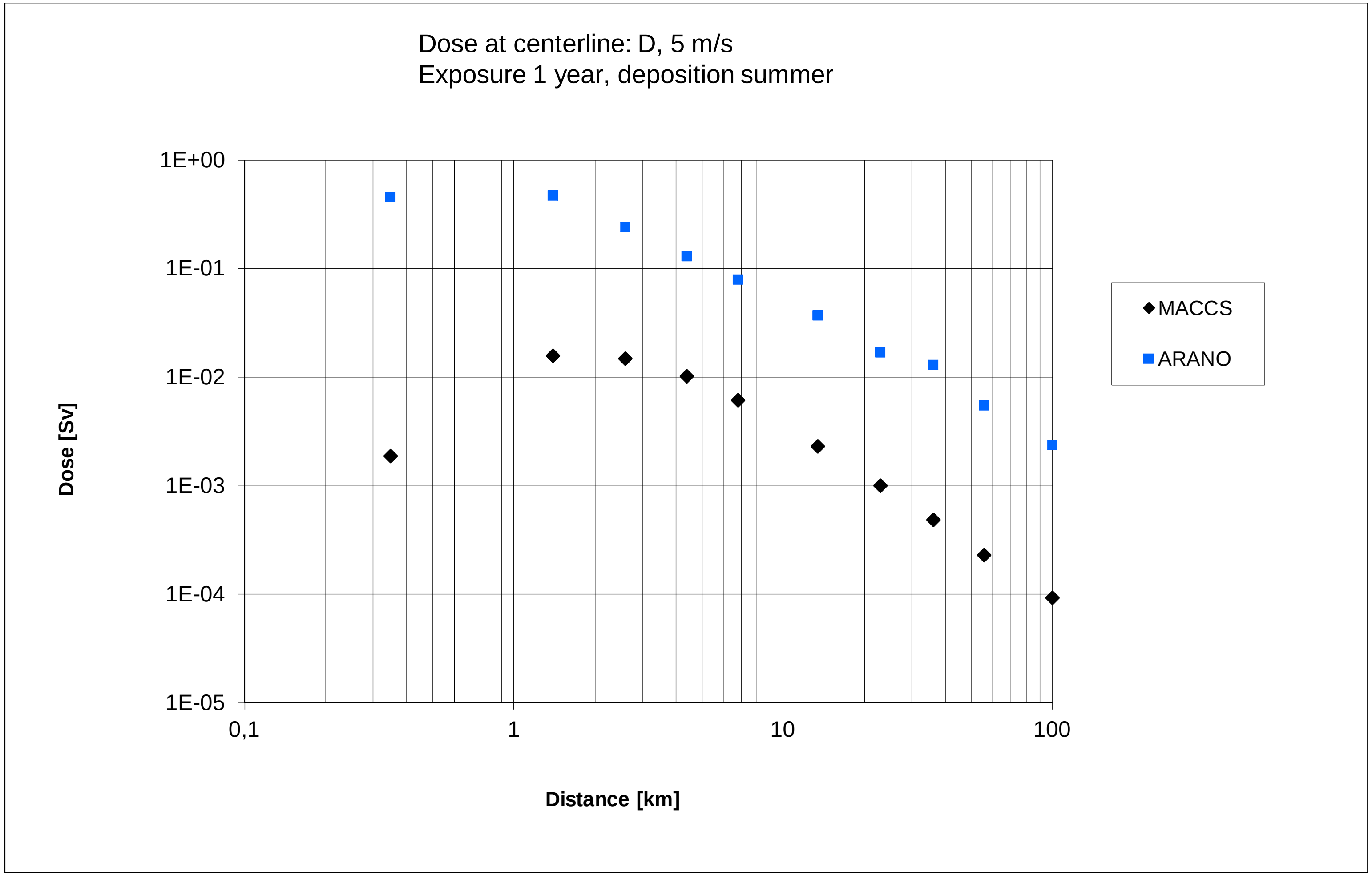
- ARANO lower up to 30 km in the stable condition

Single weather comparison runs, Ingestion exposure pathways

- Stability D, wind speed 5 m/s, no rain
- Consumption time 1 year, DC factors 50 a (adult)
- ARANO considers milk, meat, grain, green vegetables, roots
- Local (Finland) parameter values included in MACCS COMIDA2
- Some ingestion / single weather cases:

	Stability	Wind (m/s)	Nuclide (t ½)	Season
1	D	5	Cs-137 (30.17 a)	Summer
2	D	5	Cs-137	Winter
3	D	5	I-131 (8 d)	Winter
4	D	5	I-131	Summer

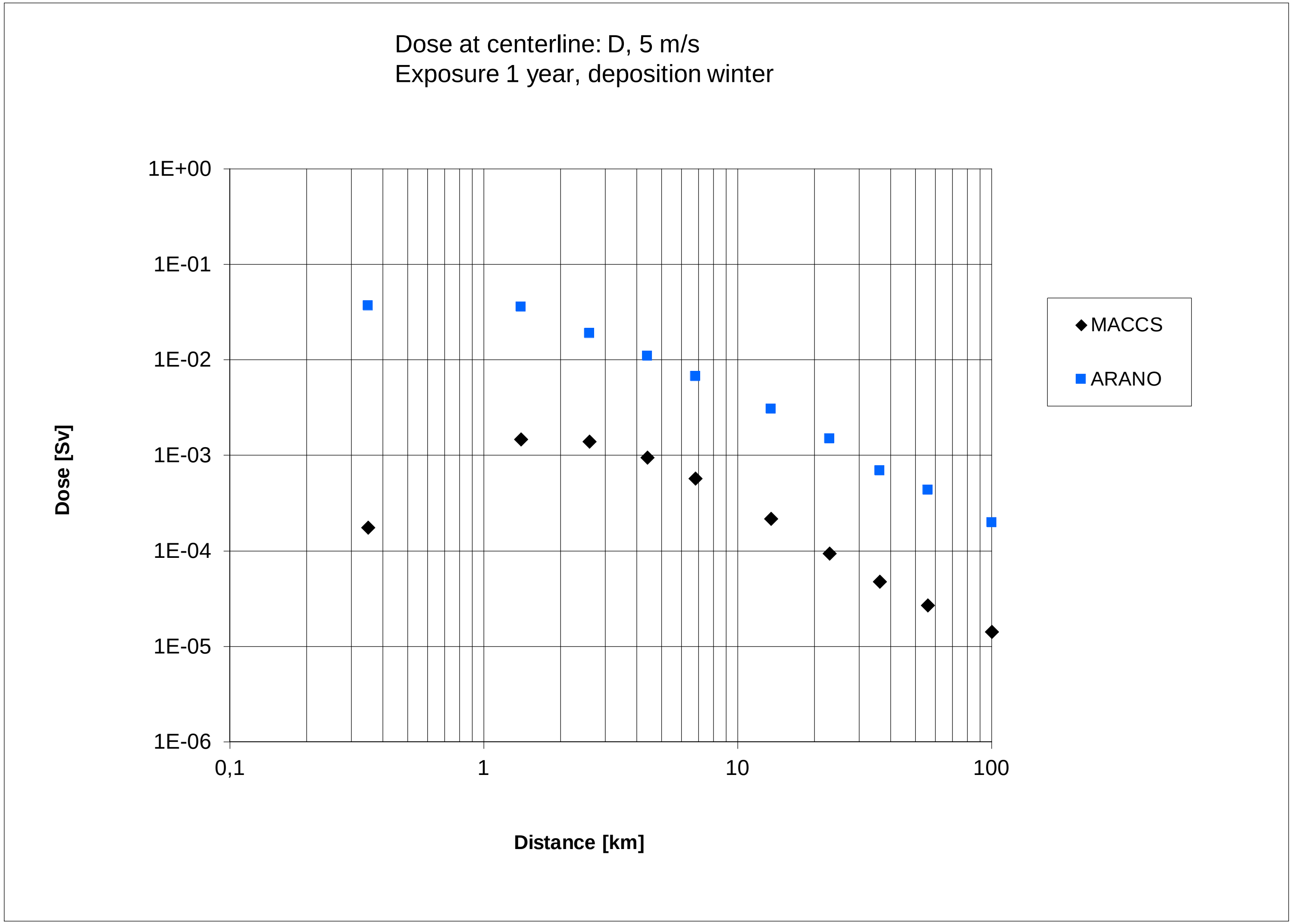
Single weather, ingestion pathways Cs-137 release, summer ('1')



- Cs-131 (half-life = 30.17 a)
- Stability D
- 5 m/s
- No rain
- 1 year consumption

- ARANO higher, mostly 10x

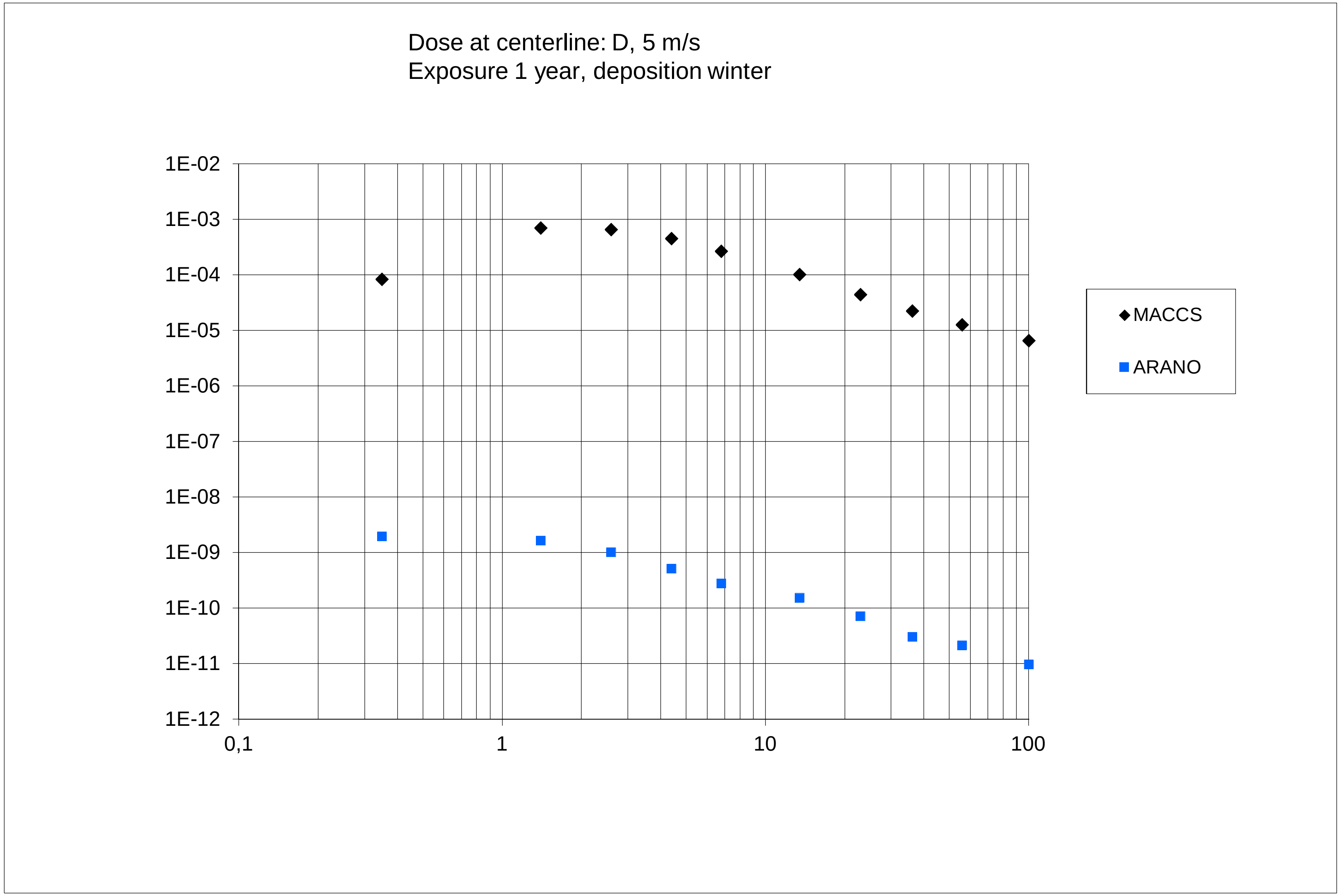
Single weather, ingestion pathways Cs-137 release, winter ('2')



- Cs-131 (half-life = 30.17 a)
- Stability D
- 5 m/s
- No rain
- 1 year consumption

- ARANO higher, mostly 10 m

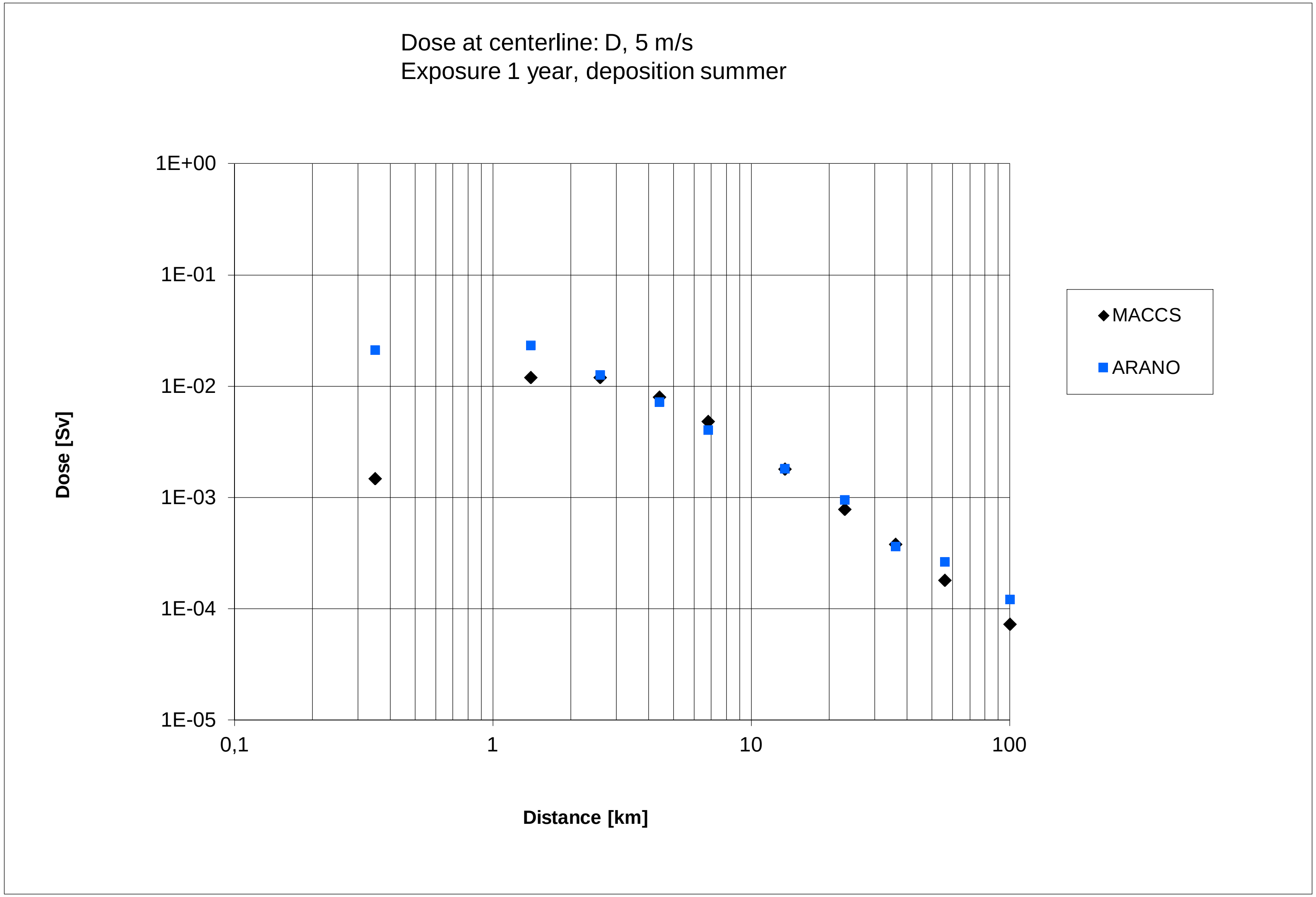
Single weather, ingestion pathways (winter) I-131 release; cow milk and meat dominating



- Iodine
- Stability D
- 5 m/s
- No rain
- 1 year consumption

- ARANO lower (1E6 x)
- Probably growing season not the same in the models?

Single weather, ingestion pathways (summer) I-131 release; cow milk and meat dominating



- Iodine
- Stability D
- 5 m/s
- No rain
- 1 year consumption

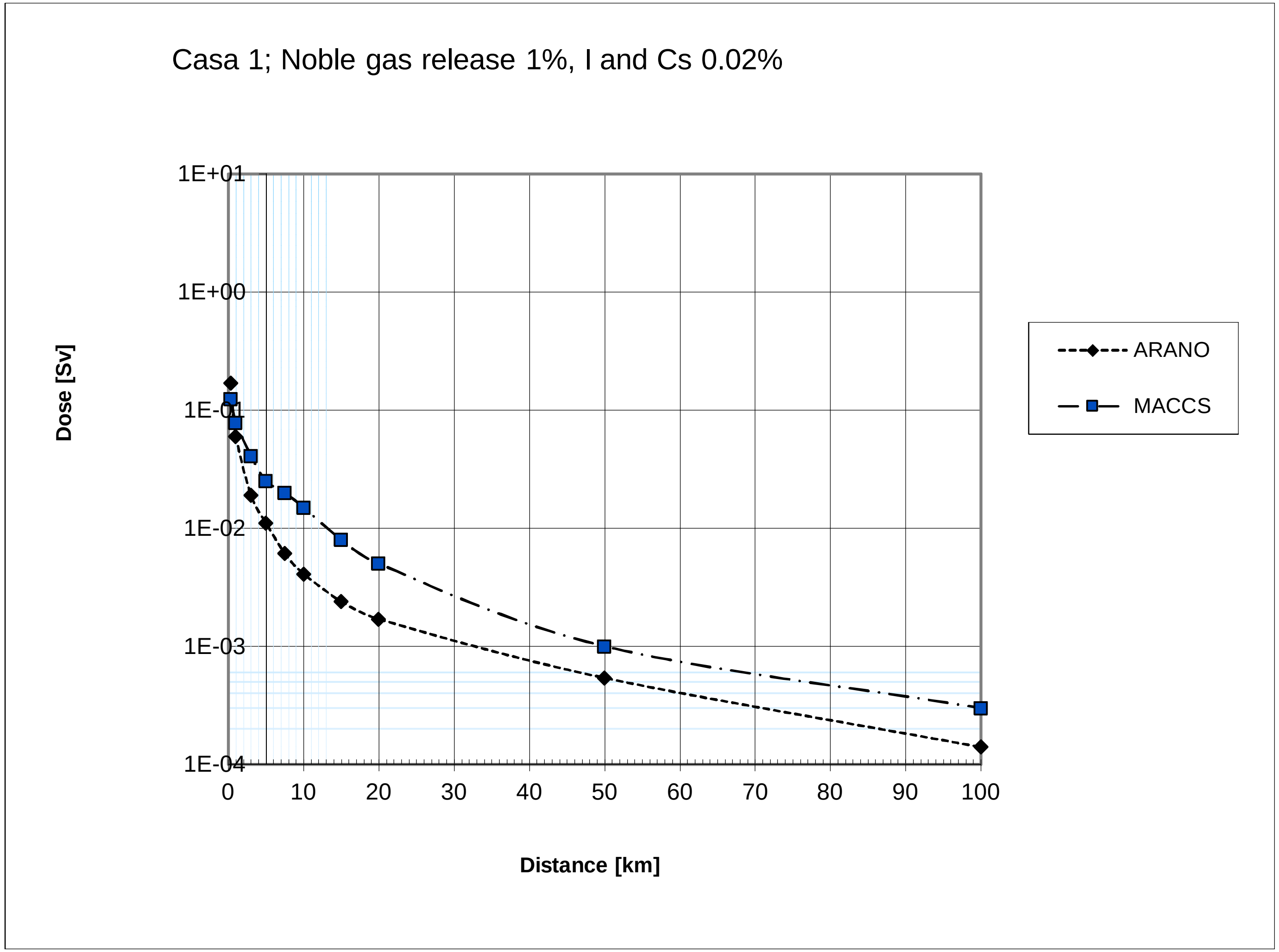
- ARANO higher at < 3 km and > 20 km

CCDF (one year weather) results, ’95 %’ Integration / consumption time 1 year

- Olkiluoto site, weather mast data (2009)
- CASA project source terms [Rossi, Ilvonen 2015] were used:
  - Case 1: ‘CASA1’, noble gases 1%, I-131 1000 TBq, Cs-137 100 TBq (Severe accident release limit in Finland)
  - Case 2: ‘CASA2’, noble gases 20%, iodine + caesium 2%
  - Case 3: ‘CASA3’, noble gases 100%, iodine + caesium 20% (‘No containment’)

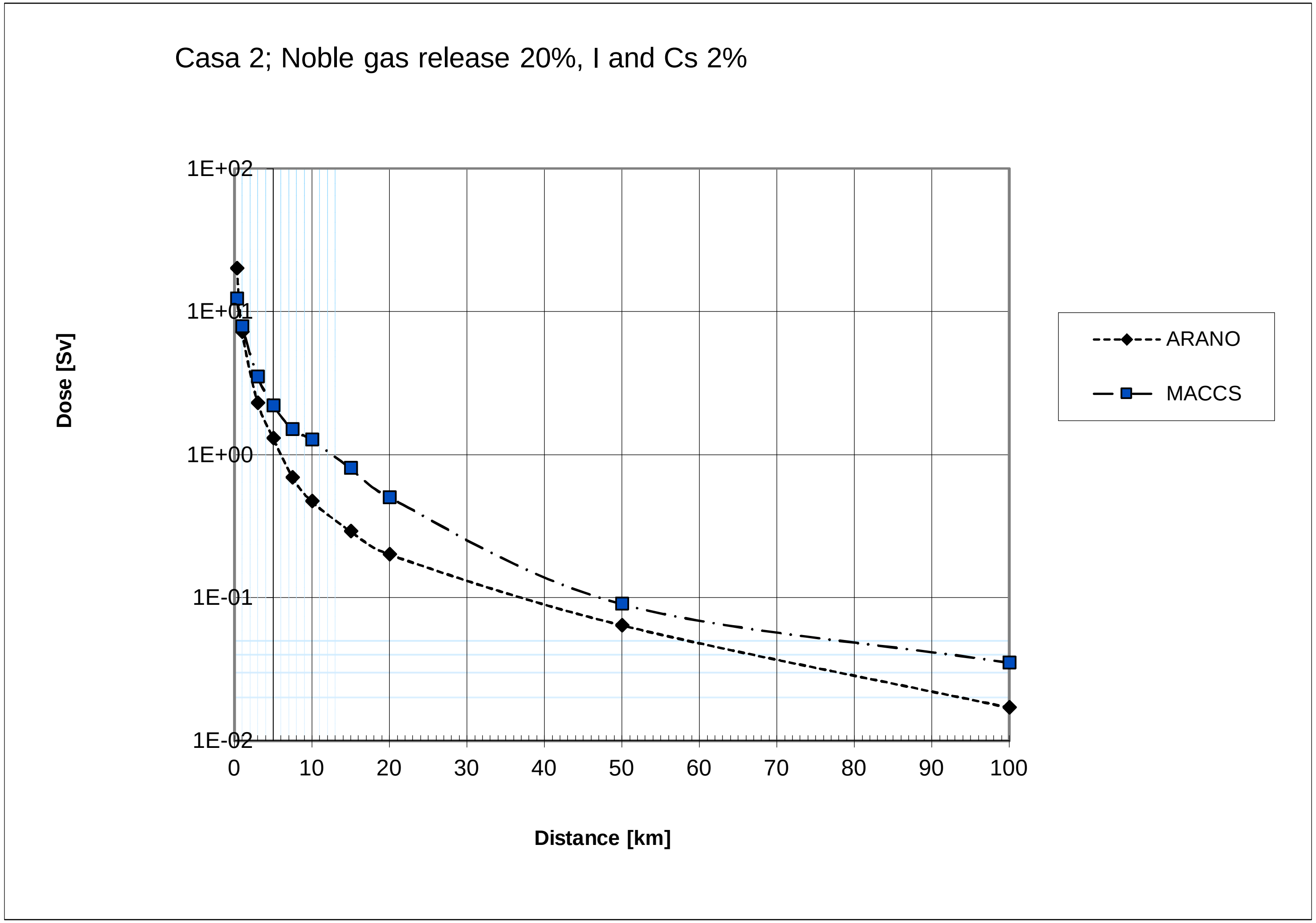
	Source term	Exposure path	Models
1	CASA1	Non-ingestion	ARANO, MACCS
2	CASA2	Non-ing.	ARANO, MACCS
3	CASA3	Non-ing.	ARANO, MACCS, VALMA
4	CASA1	Ingestion	ARANO, MACCS, VALMA

The dose of the 95 % fractile from the CCDFs, As function of distance, Non-ingestion paths, ’1’



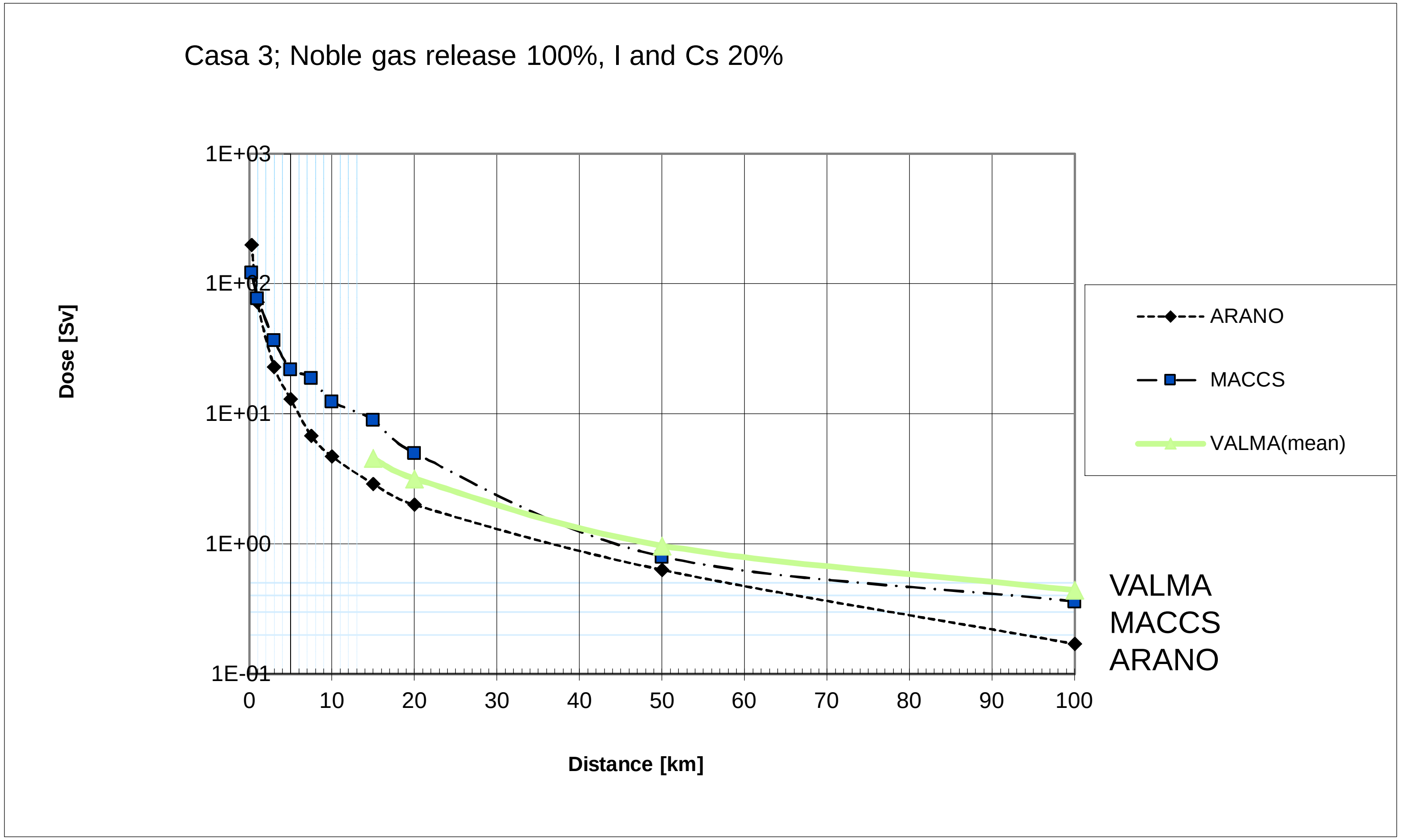
- Source term ’CASA1’
- One year integration for groundshine
- ARANO doses consistently lower than MACCS

The dose of the 95 % fractile from the CCDFs, As function of distance, Non-ingestion paths, ’2’



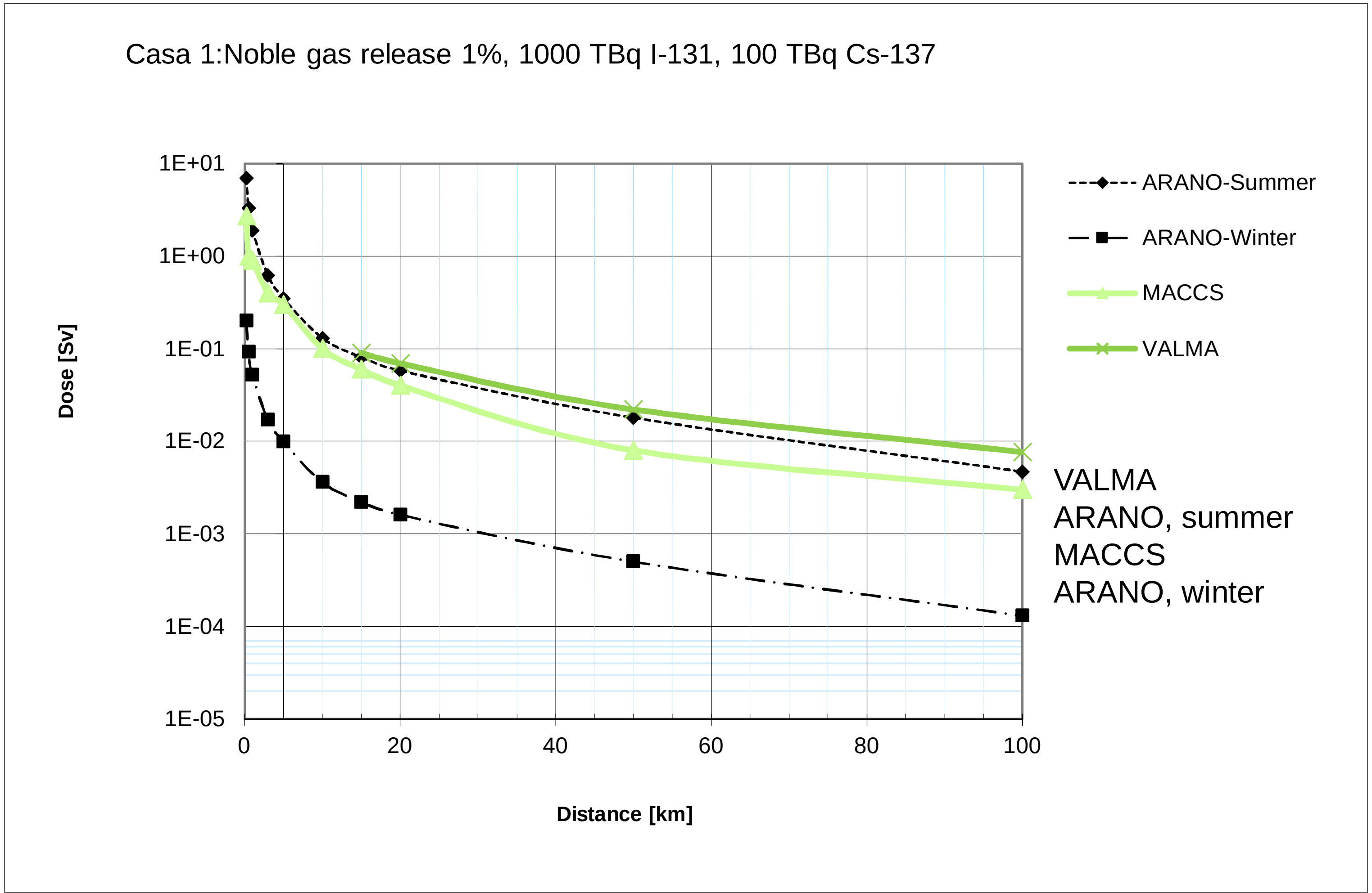
- § Source term ’CASA2’
- § One year integration for groundshine
- § ARANO doses consistently lower than MACCS

The dose of the 95 % fractile from the CCDFs, As function of distance, Non-ingestion paths, ’3’



- Source term ’CASA3’ (no containment)
- One year integration for groundshine
- VALMA available only 15 km and beyond in this case

The dose of the 95 % fractile from the CCDFs, As function of distance, Ingestion paths, '4'



- Source term 'CASA1'
- One year consumption
- VALMA only 15 km and beyond in this case

Comparison of ARANO, MACCS and VALMA -Conclusions on dose results

- Two kinds of comparisons were made:
  - Chosen single dispersion conditions
  - One year's weather data (measured hourly by met. mast)
- Compared were two kinds of doses:
  - Cloudshine + groundshine (1 week / 1 year) + inhalation
  - Ingestion doses
- ARANO typically predicts smaller dose values than MACCS.
- In most cases, ARANO predicts higher doses near the source than MACCS; for ingestion, difference can be either way
- Significant differences in single dispersion situations
- When the dose at e.g. 95% fractile is considered, the difference is at most less than a factor of three.
- Comparable dose estimates of VALMA predict smaller dose values than MACCS at distances up to 15 km.
- This comparison indicates that MACCS in many cases calculates conservative dose estimates?

Comparison of ARANO, MACCS and VALMA includes effects of weather source (VTT-R-00136-19)

- VALMA used SILAM-based meteorological data for Olkiluoto (2012)
- ARANO and MACCS were used with mast-based meteorology (parameters measured at the Olkiluoto NPP weather mast).
- VALMA can also be used with single-points measurements, but that is not the recommended use, if SILAM data is available.
- ARANO and MACCS differ in how they use the measured params:
- ARANO mixing height follows from the vertical profiles of the Kz model, and it is basically a function of atmospheric stability.
- MACCS uses only seasonal average mixing heights.
- ARANO uses wind speeds for the release height.
- MACCS wants wind speeds for its fixed reference height, and then calculates the needed speed for the actual release height from a logarithm formula.
- It is evident that the meteorological parameters alone could be responsible for significant differences in results.

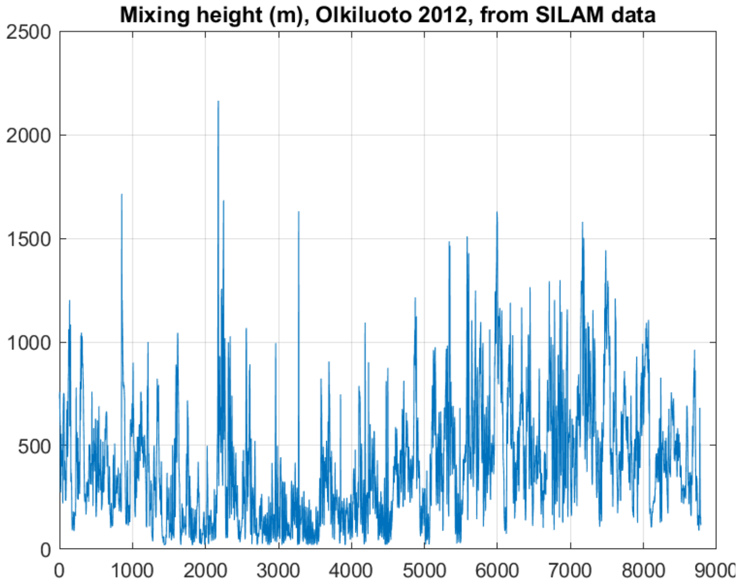
Some problems with WinMACCS encountered at VTT

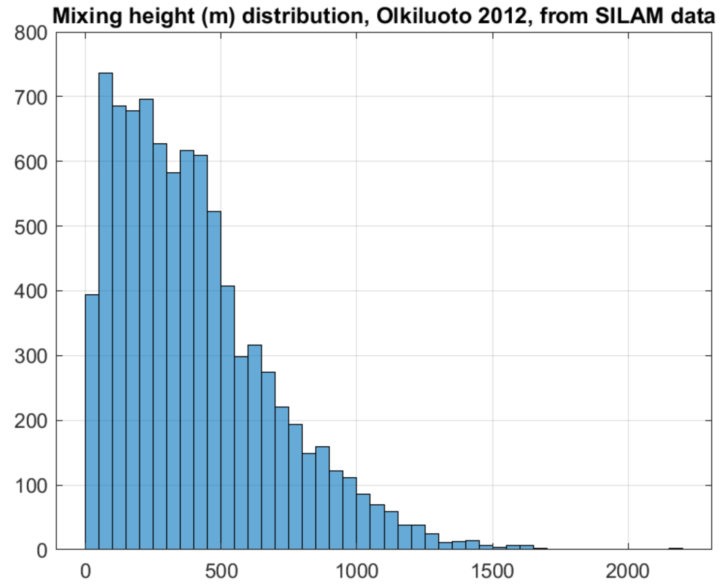
(Note: Maybe we didn’t so far understand all the proper procedures.)

- Installation, upgrading of project input files:
  - 3.11.2 won’t install (‘Visual Basic 6.0 Setup Toolkit: Run-time error – method of object failed.’)
  - Upgrading project inputs from 3.10.2 to 3.11.2 not successful
  - Type mismatch of the forms’ numerical input fields (decimal symbol / digit grouping symbol?)
- Exposure pathways, integration times (cf. IAEA GSR Part 7, App. II):
  - Doses to fetus & tissue (0.5 cm under skin) needed
  - Exposure integration time 10 h is needed
  - What is the fidelity of predictions in the very near field (< 500 m) ?
- Practical: Batch running, extraction of results
  - Should we use cyclic run to easily get results for a number of exposure pathways
  - Should we extract the results for further use from the result file manually or by writing a dedicated code

Mixing height and stability class from SILAM

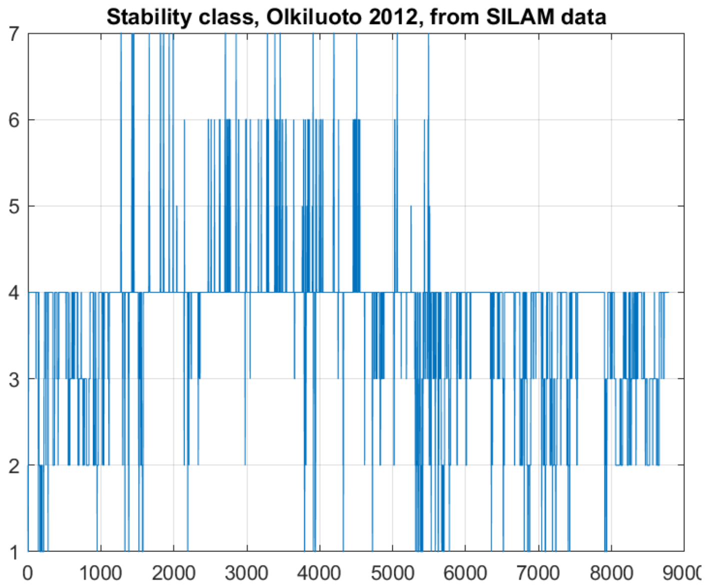
- Mixh
- F(t)

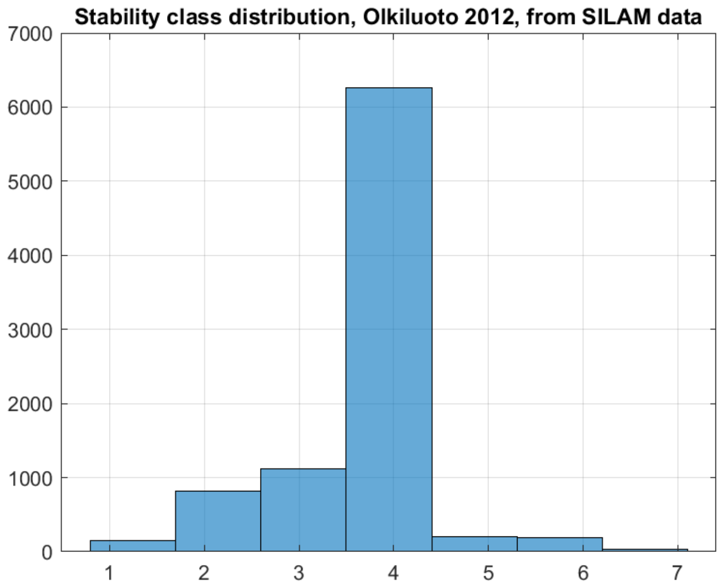




Mixh: Distribution

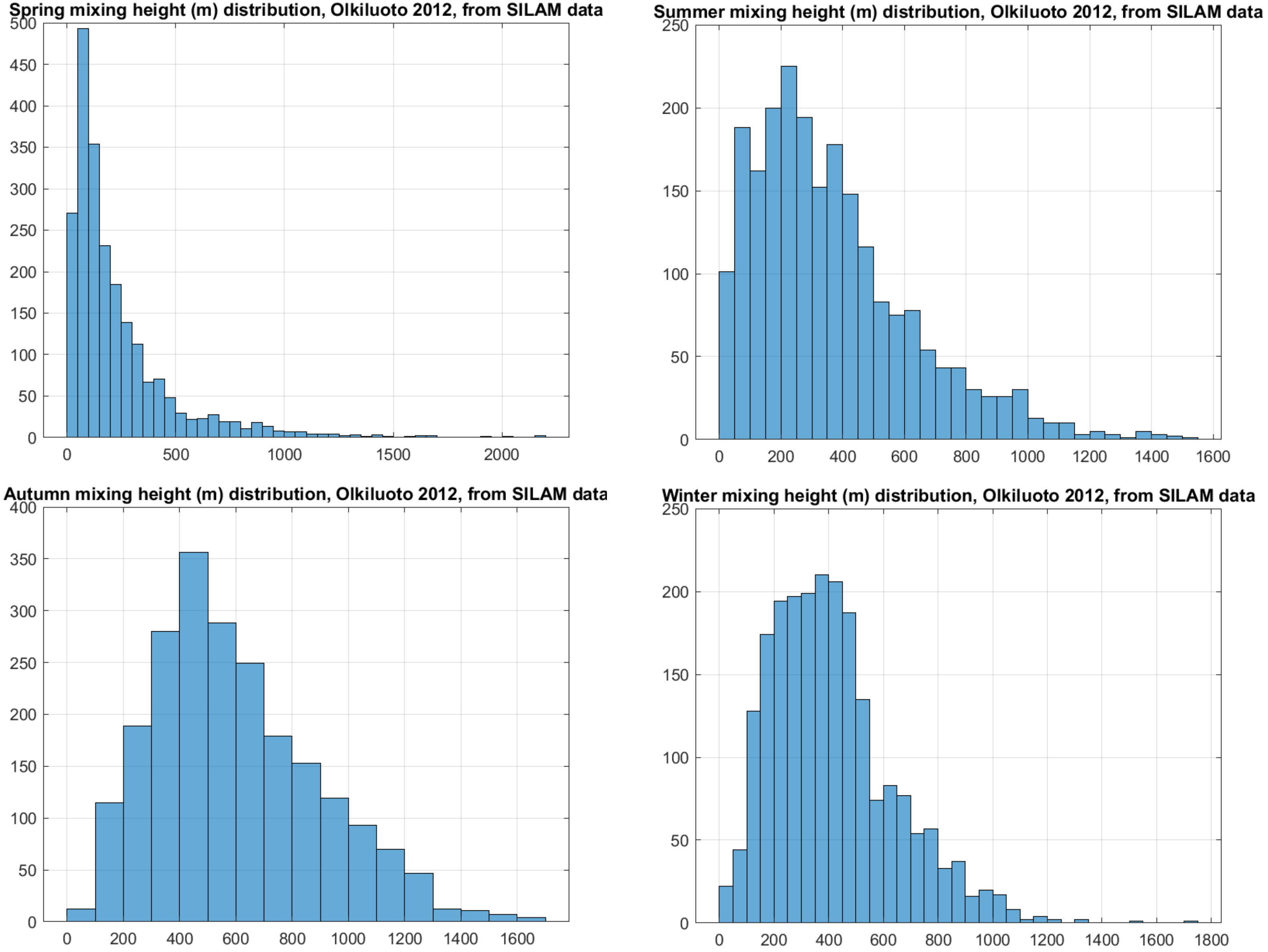
Stability: F(t)





Stability: Distribution

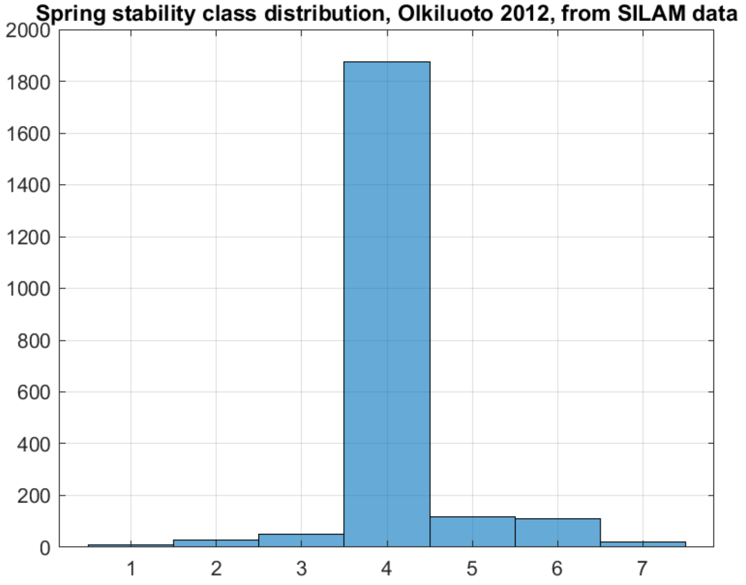
SILAM mixing height by seasons

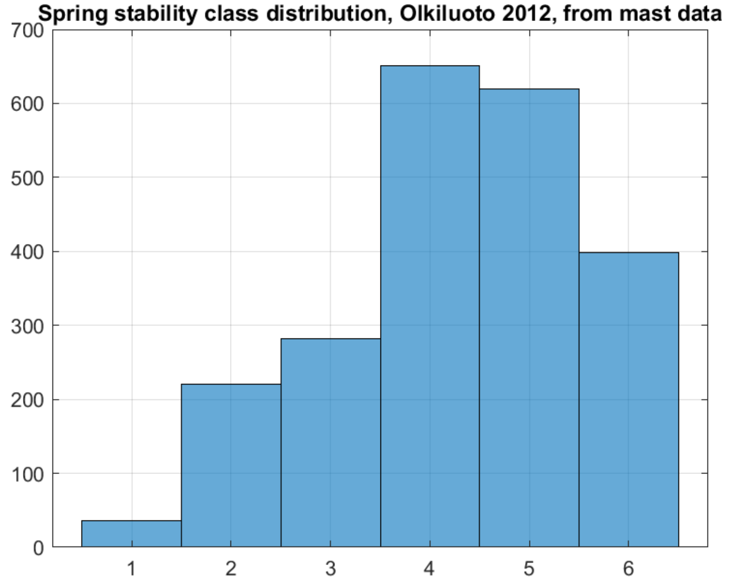


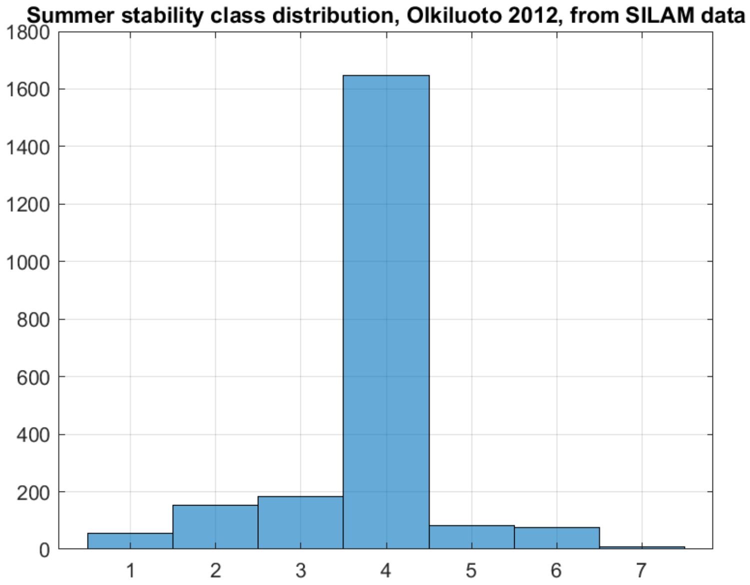
Stability class from weather mast measurements

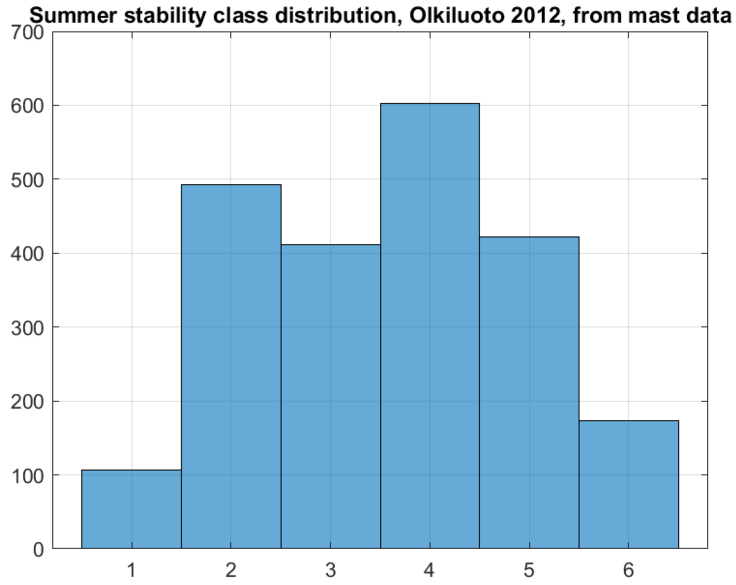
1. Temperature differences (used in this work)
2. Wind direction variations
3. Based on Monin-Obukhov length

Spring and summer stability class distribution: SILAM vs. mast temp diff

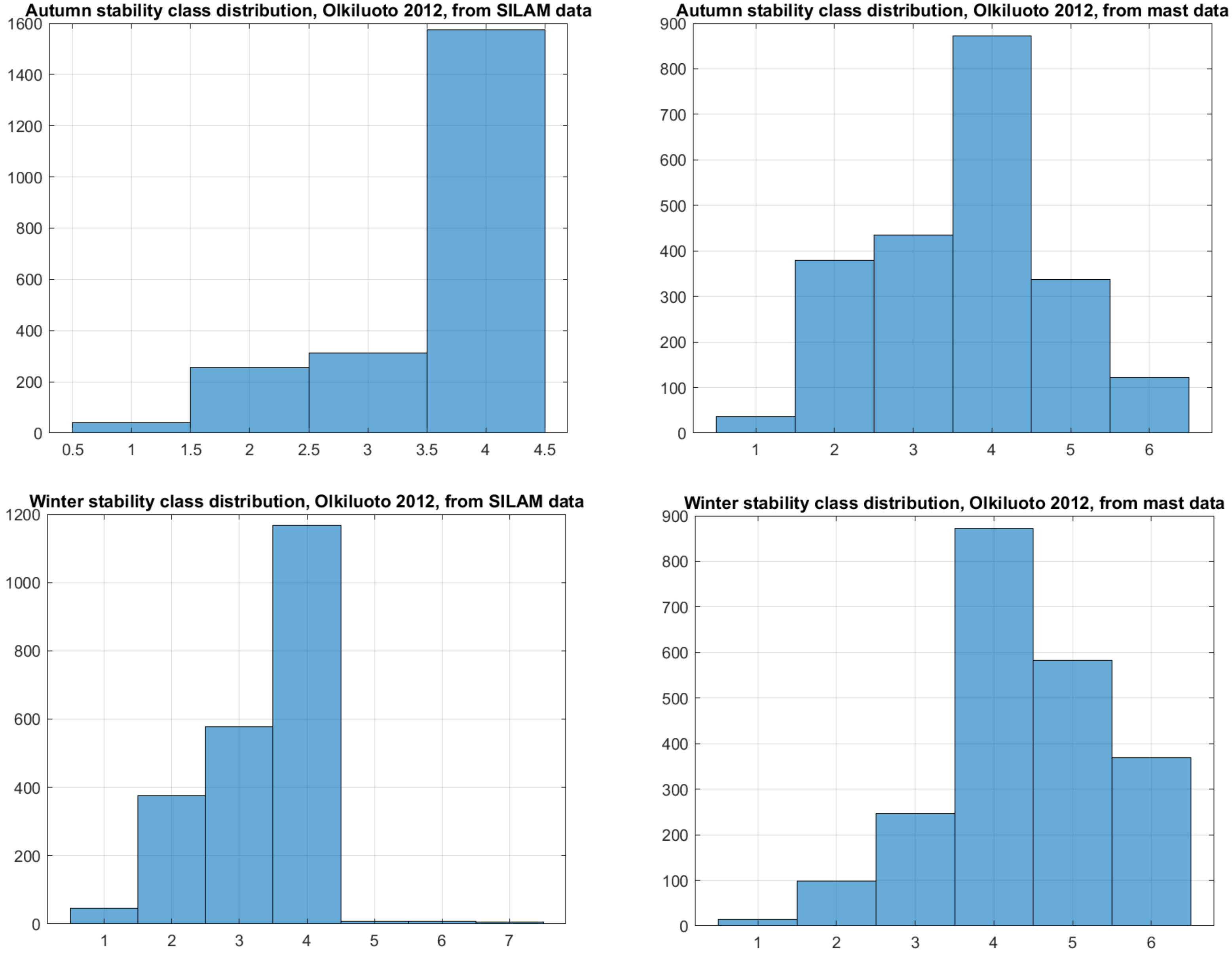








Autumn and winter stability class distribution: SILAM vs. mast temp diff



VTT creates business from technology