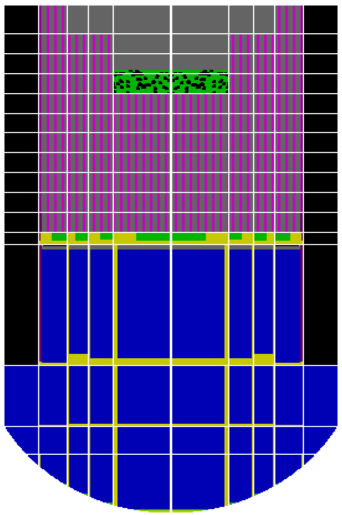

Comprehensive Analysis of Severe Accidents

SAFIR2018 INTERIM SEMINAR AND WEBINAR

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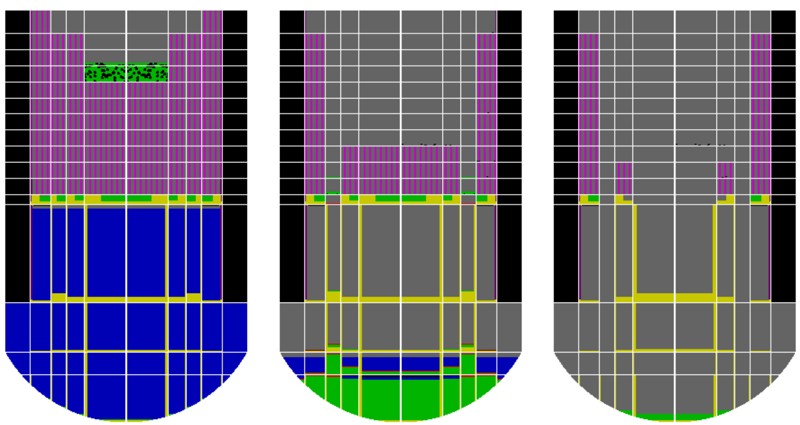
Contents

Analysing Fukushima accidents 1/2

The Fukushima accident provides a unique opportunity for gaining more information on the progress of severe accidents and their prevention and mitigation.

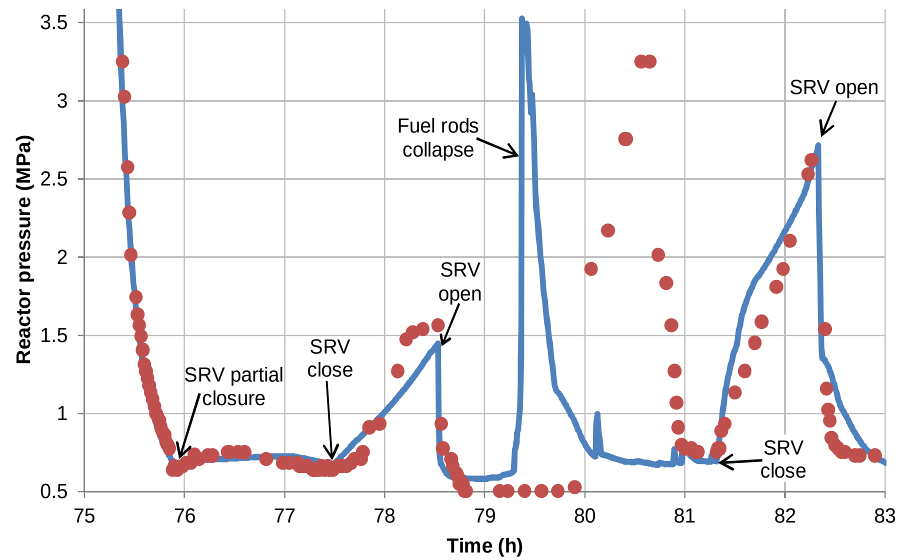
- The objectives in analysing the accidents are:
    1. Improving expertise in severe accident modelling, using data from a real full-scale reactor accident
    2. Gaining a better understanding of the events in the Fukushima reactors
    3. Getting insights into the capabilities and weaknesses of the integral codes in simulating severe accidents
- VTT participates in OECD BSAF-2 project (Benchmark Study of the Accident at Fukushima)



State of the Unit 3 reactor at 41 h 52 min, 43 h 44 min, and 72 h.

Analysing Fukushima accidents 2/2

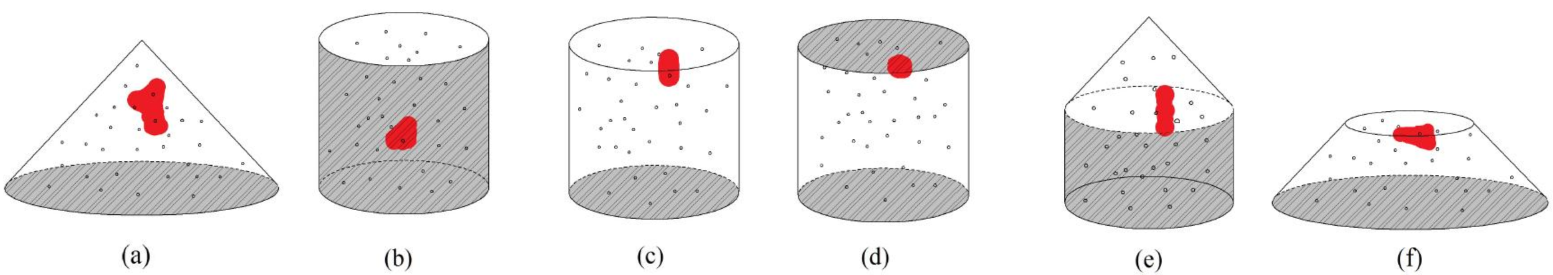
- VTT has developed MELCOR models for all three units that have been updated when new plant data has been published
- All models reproduce the primary circuit pressure behaviour and water level well in the beginning of the accident (up to 36–80 h)
  - RCIC (Reactor Coolant Isolation Cooling) and HPCI (High-Pressure Coolant Injection) system flow rates were manually adjusted
  - Operation of SRV (Safety Relief Valve)
- To have good correspondence in the containment pressure some leaks were assumed
  - A small leak from the recirculation pump seal to the drywell in Unit 3 and Unit 1
  - Major leakage through the drywell head in Unit 2



Unit 2 reactor pressure.

Debris bed coolability 1/2

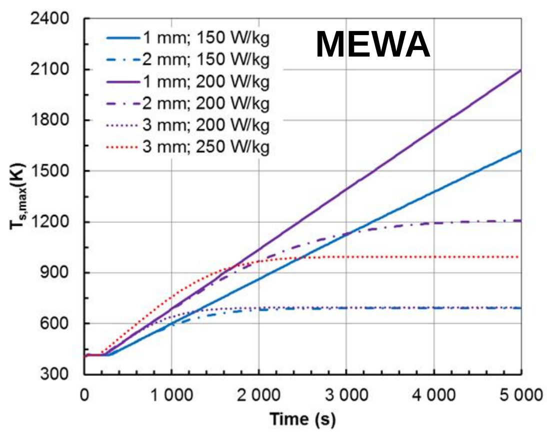
- COOLOCE experiments to analyse the effect of debris bed geometry and flooding mode on dryout heat flux were performed already in the frame of SAFIR2014
- The experimental and analytical results were summarized in the Doctoral Thesis of Eveliina Takasuo
- The main results were:
  - The coolability of the debris bed depends on both the flooding mode and the height of the bed
  - Multi-dimensional flooding increases the dryout heat flux and coolability in a heap-shaped debris bed by 47–58% compared to the dryout heat flux of a classical, top-flooded bed of the same height
  - Heap-like beds are higher than flat, top-flooded beds, which results in the formation of larger steam flux at the top of the bed. This counteracts the effect of the multi-dimensional flooding
  - The maximum height of a heap-like bed can only be about 1.5 times the height of a top-flooded, cylindrical bed in order to preserve the direct benefit from the multi-dimensional flooding

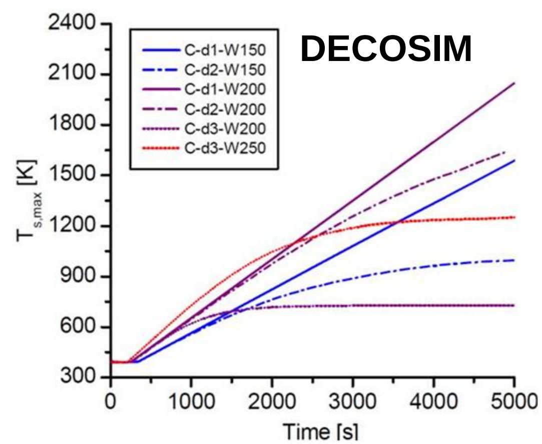


Dryout locations in the experiments.

Debris bed coolability 2/2

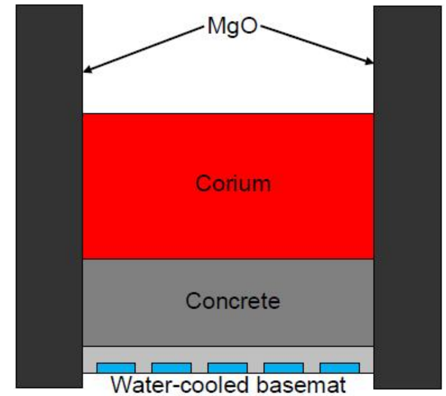
- The coolability limit based on the minimum dryout heat flux might be overly conservative
  - The temperature may remain on an acceptable level even in the dry zone
- Instead of the dryout heat flux, it has been proposed that the coolability limit should be based on the increase of the particle temperature
- The VTT's MEWA results on post-dryout temperature behavior in a debris bed were compared to KTH's DECOSIM results and notable differences were found
  - For small particle cases without temperature stabilization, the codes agree satisfactorily
    - Expected that the maximum particle temperature eventually exceeds the temperatures where zirconium oxidation or even corium remelting begins
  - In the other conical bed cases the beds are coolable
    - Codes predict different transient behaviours and final steady-state conditions





Predicting heat transfer in ex-vessel melt pools 1/2

- Three different experiments analysed:
  1. WCB-1 (Water Cooled Basemat): melt coolability in a core catcher
     - 400 kg of melt heated by electricity and a layer of sacrificial concrete on top of an inert MgO crucible with cooled basemat
  2. SSWICS (Small-Scale Water Ingression and Crust Strength)
     - 60–80 kg of melt without taking decay heat into account in an inert MgO crucible
  3. CCI (Core-Concrete Interactions)
     - 400 kg melt heated by electricity and gas bubbling through melt from decomposing concrete

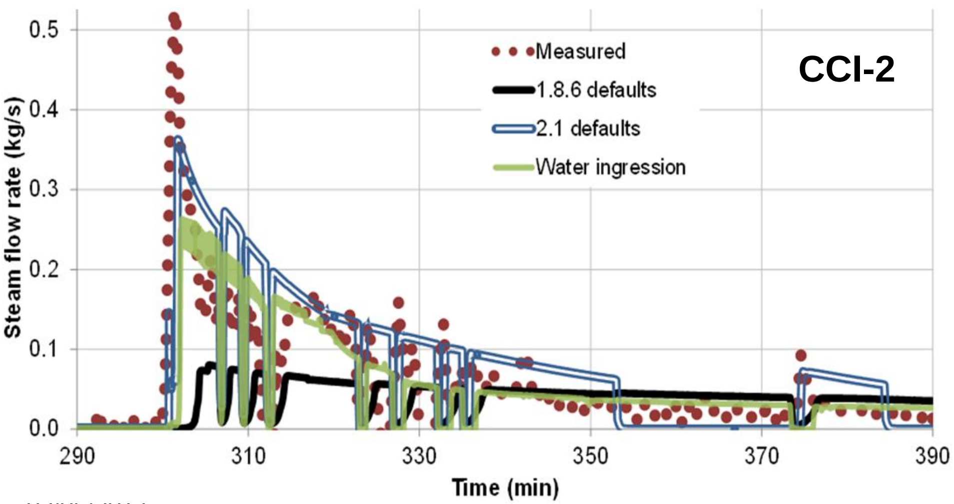


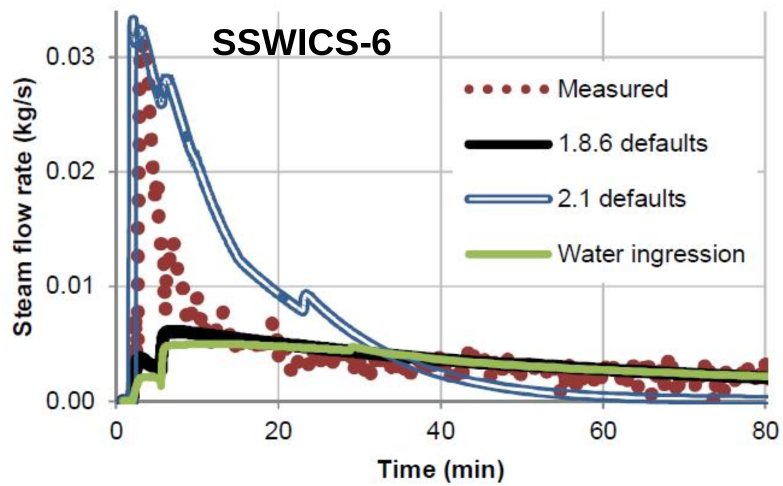
- Heat transfer coefficients in the WCB-1 experiment were compared with free convection correlations
  - Commonly used Steinberner & Reineke correlations overestimate the average heat transfer coefficient upwards by a factor of 2 and downwards by a factor of 3
  - Up/down power split underestimated by a factor of 1.5

    → Accident analyses based on these correlations would be conservative with respect to containment pressure and heat flux to cooling channels, but non-conservative with respect to melt temperature and solidification

Predicting heat transfer in ex-vessel melt pools 2/2

- The new water ingression model implemented in the MELCOR version 2.1 was tested analysing seven SSWICS and two CCI experiments
  - Compared to version 1.8.6 default model in which water ingression was not taken into account and to version 2.1 default settings where water ingression is attempted to model by heat transfer multipliers
- Satisfactory results in the CCI experiments with the new model in which gas bubbles were released to the melt from decomposing concrete
- The new model had little effect in the SSWICS experiments that were done without gas bubbling through the melt

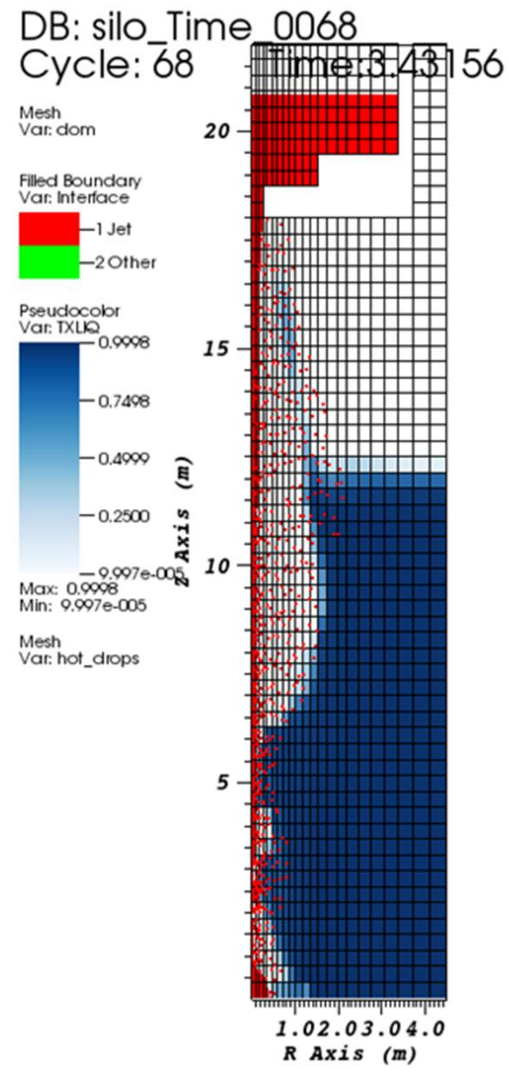




Ex-vessel steam explosion analyses with MC3D 1/2

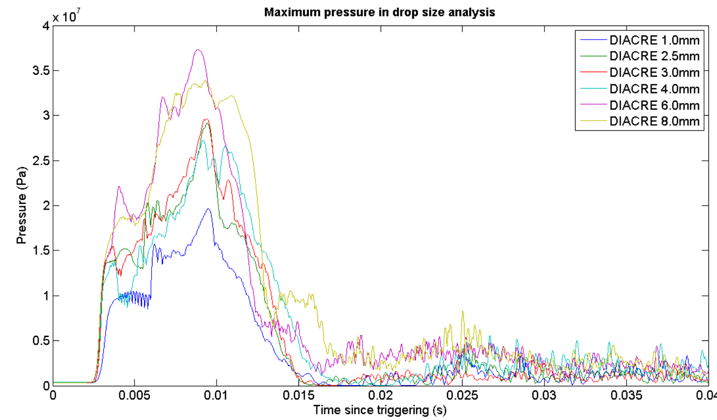
Preserving of knowledge of steam explosions is important still today, since the risk of steam explosions during a severe accident cannot be excluded in our current nuclear power plants.

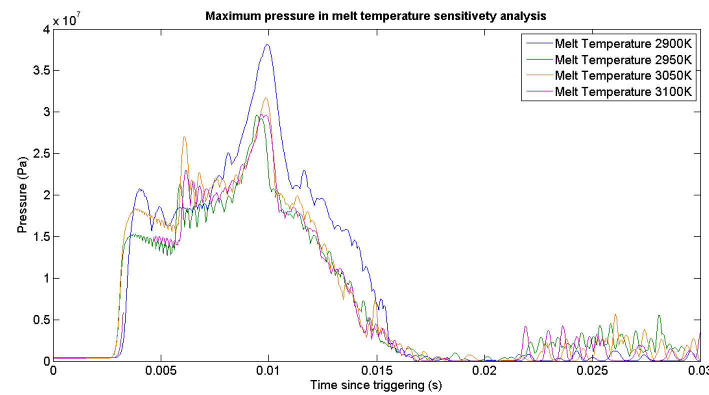
- The steam explosion loads were assessed with the MC3D code studying the sensitivity of the results for some key input parameters
- Simulations were firstly made to analyse the effect of different triggering times
    - The results showed that as long as the mixture is triggerable, the resulting explosions are fairly similar
- The sensitivity analysis was done for melt drop size, melt temperature, cavity water level and coolant temperature



Ex-vessel steam explosion analyses with MC3D 2/2

- Drop size had the largest impact on both explosion strength and probability
  - With larger drops, explosions became more probable and also stronger
- Melt temperature was not observed to effect the explosion strength
  - Only melt above liquidus temperature resulted in an explosion
  - Melt was overheated and there was no time for solidification
- Higher water level generated stronger explosions
  - Larger region with drops in coolant compared to the lower water level cases
- Coolant temperature effect was not straightforward
  - Higher subcooling level could cause stronger explosions

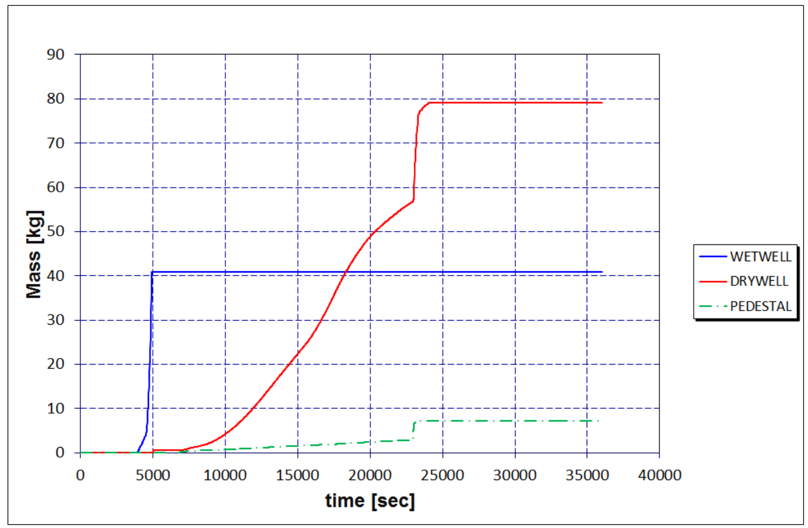




Hydrogen fire risk in the containment

- The risk of a flammable mixture of hydrogen and air to be formed in the reactor building was studied analysing a SBO scenario for the Nordic BWR plant with MELCOR
  - Results showed such low concentrations that a hydrogen fire is very unlike, when there was not assumed an increase in the containment design leak
  - Local concentrations might become high enough to cause a hydrogen fire
    - The total mass of hydrogen in the reactor building remained low
      - → Assorted energy release would not be high
      - → Not considered as an explosion

- Also a SBO accident with a non-inerted containment was analysed
  - Resulted in hydrogen deflagrations in the containment
  - Did not proceed into detonation, i.e. into an explosion
  - Caused increase in temperature but not in pressure
    - → Burning of hydrogen consumes gas which decreaseses the pressure



Mass of burned H_2 in non-inerted containment.

Defining in-containment dose rates 1/2

- Radiation dose might affect:
  1. The operation of instrumentation and automation systems
  2. Leak-tightness of containment penetration seal materials
  3. Formation of nitric acid in the containment (beta and gamma radiation)

     → Reduces the pool pH decreasing iodine retention in pools

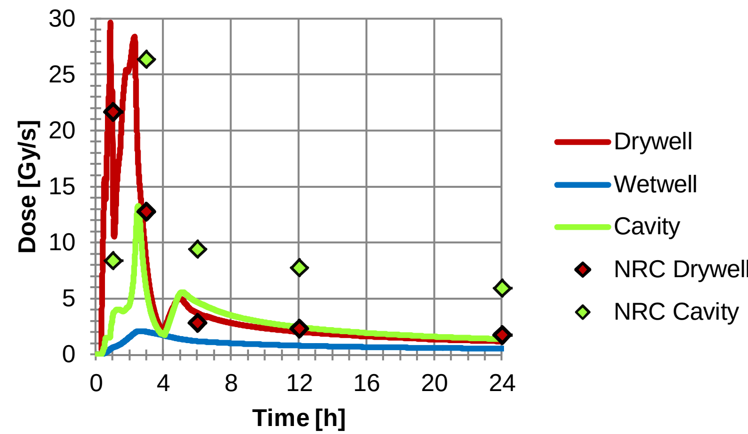
- The objective was to compare the dose rates in containment produced by integral code ASTEC and by NRC method

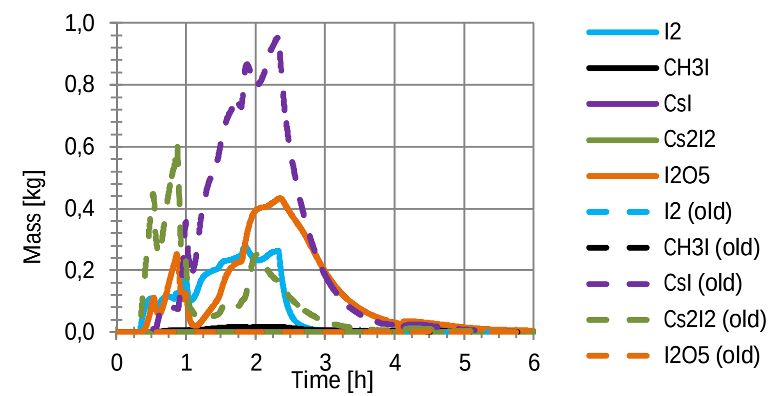
Contribution of different elements to beta and gamma dose rates according to ASTEC:

Beta dose in the drywell gas phase				
Time	**Xe**	**Kr**	**I**	**Cs**
1 h	0.17	0.23	0.36	0.10
3 h	0.34	0.20	0.36	0.02
6 h	0.18	0.04	0.69	0.04
12 h	0.24	0.02	0.68	0.06
24 h	0.29	0.00	0.62	0.09
Gamma dose in the drywell gas phase				
Time	**Xe**	**Kr**	**I**	**Cs**
1 h	0.05	0.54	0.31	0.06
3 h	0.08	0.67	0.23	0.01
6 h	0.09	0.37	0.48	0.06
12 h	0.13	0.28	0.49	0.10
24 h	0.15	0.30	0.40	0.15

Defining in-containment dose rates 2/2

- The gas phase dose rates produced by NRC method were expected to be higher than the ASTEC dose rates
  - The deposited fission products were included in the gas phase inventory
  - ASTEC assumes that 50 % of the radiation from the deposited fission products is absorbed by the wall
- The difference was higher than expected for all but drywell beta dose rate
- It is assumed that ASTEC does not take into account the decreasing gas phase volume due to cavity flooding
- In all cases the total dose rate estimates were within a factor of two that can be considered rather acceptable
- ASTEC input was also changed by increasing the wet painted wall area in the containment
  - Increased the mass of I_2 and iodine oxides
    - Assumed to result from organic iodides radiolytically destructing into I_2 and I_2 then reacting with air radiolysis products to form iodine oxides
- The change in iodine behaviour resulted slightly higher dose peaks in the containment gas phase but notably smaller dose rates on walls

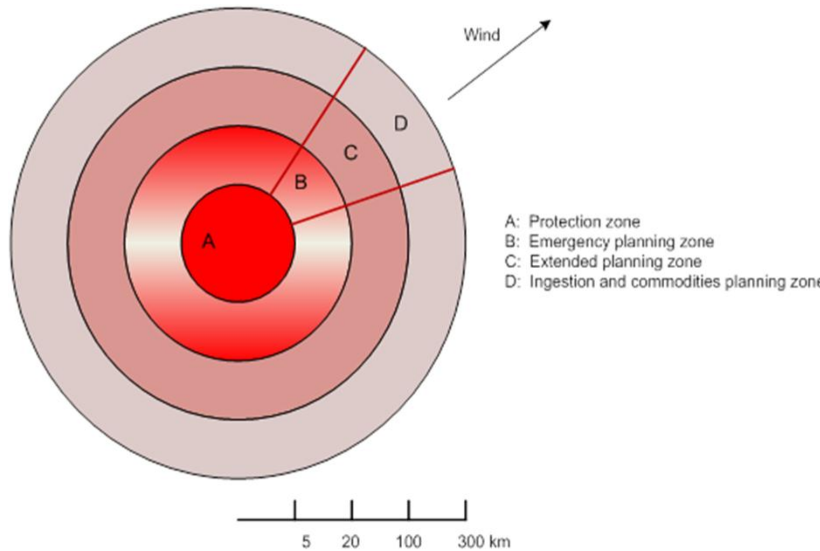




Environmental consequences 1/2

As a consequence of Fukushima accident IAEA started to develop recommendations which consider emergency planning beyond 20 km.

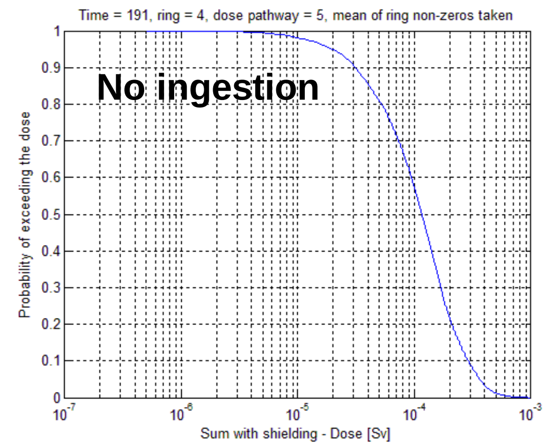
- VALMA was further developed by implementing there the ingestion dose pathways (green vegetables, grain, root vegetables, cow milk and cow meat)
    - Dispersion and dose assessment code able to use realistic weather data purposed to serve as an emergency preparedness tool
- Probability distributions of radiation doses from different exposure pathways at distances up to 300 km were determined using three different release magnitudes:
    1. 1 % of noble gas inventory, 1000 TBq for I^{131} and 100 TBq for Cs^{137}
    2. 20 % of noble gas inventory and 2 % of iodine and caesium inventory
    3. 100 % of noble gas inventory and 20 % of iodine and caesium inventory

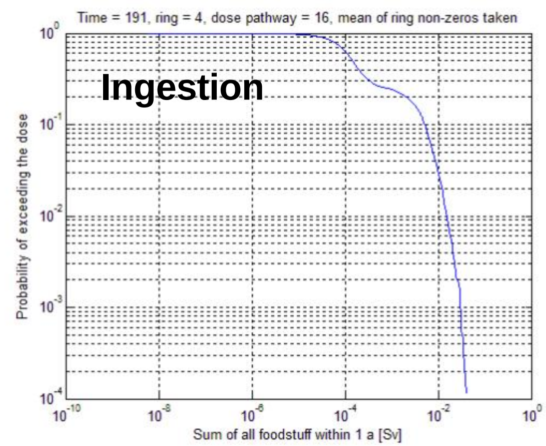


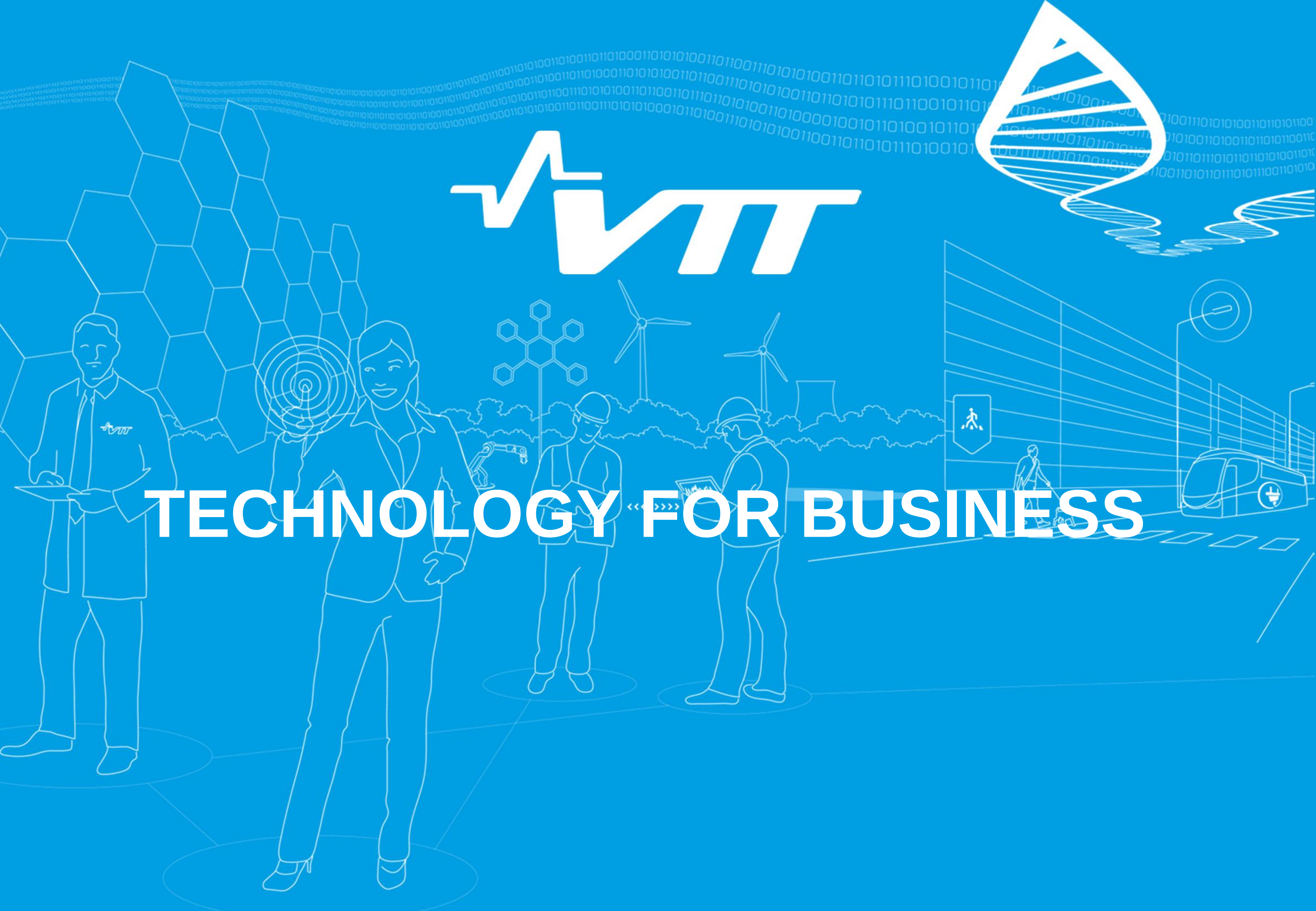
Maximum Cs release of activity in a severe accident according to YVL-guides

Environmental consequences 2/2

- The total ingestion dose was approximately 20 times higher than the dose from non-ingestion pathways
  - For one year time period
- For the maximum severe accident activity release (case 1):
  - Ingestion dose under 10 mSv with the probability level of 95 % at the distance of 100 km
    - → Countermeasures on food consumption would not be necessary
  - Total dose is little below 100 mSv at the distance of 20 km
    - → The prevailing release limit is reasonable
- If the release magnitude exceeds significantly the criterion of the severe accident (case 2 and 3)
  - Ingestion dose may increase over 10 mSv at 100 km
  - Dose level of 100 mSv from non-ingestion pathways might be exceeded beyond 20 km
    - → Countermeasures should be recommended in both cases



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