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Assessment of activity inventories in Swedish LWRs at time of decommissioning

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	O2: Activity [Bq]		
ilding	R	T	Total
H-3	3.5E+14		3.5E+14
C-14	4.6E+12	1.3E+09	4.6E+12
Cl-36	1.8E+09	2.3E+04	1.8E+09
Ca-41	5.2E+09		5.2E+09
Mn-54	9.7E+14	7.5E+09	9.7E+14
Fe-55	2.9E+16	7.3E+10	2.9E+16
Co-60	4.3E+15	8.8E+10	4.3E+15
Ni-59	3.3E+13	8.9E+08	3.3E+13
Ni-63	4.0E+15	1.1E+11	4.0E+15
Sr-90	7.6E+09	1.5E+10	2.3E+10
Nb-94	5.0E+10	7.4E+00	5.0E+10
Tc-99	4.9E+10	1.1E+07	4.9E+10
Sb-125	1.1E+12	5.7E+08	1.1E+12
I-129	2.6E+06	1.8E+06	4.3E+06
Cs-134	1.1E+11	1.4E+08	1.2E+11
Cs-135	1.3E+07	3.0E+06	1.6E+07
Cs-137	1.3E+12	6.0E+10	1.4E+12
Eu-152	3.3E+11		3.3E+11
Eu-154	1.5E+10	2.8E+07	1.5E+10
Eu-155	6.8E+09	7.9E+06	6.8E+09
Pu-238	7.2E+08	4.4E+07	7.6E+08
Pu-239	8.4E+07	6.9E+06	9.1E+07
Pu-240	1.0E+08	8.7E+06	1.1E+08
Pu-241	1.9E+10	4.4E+08	2.0E+10
Am-241	4.3E+07	3.4E+06	4.6E+07
Cm-244	8.6E+08	2.3E+07	8.8E+08
Total	3.8E+16	3.6E+11	3.8E+16
Weight [kg]	2.2E+06	1.2E+06	3.4E+06

ALARA Engineering involvement in decommissioning studies

- **OL1/2**
  - Process systems, database modification and update (2008)
- **B1/2**
  - Project “RivAkt”, Total activity assessment (2007), evaluation of performed system decontaminations (2008)
- **R1/2/3/4**
  - Total activity assessment (2007), update (2010)
- **F1/2/3**
  - Total activity assessment (2010)
- **O1/2(/3)**
  - O1/2 - Total activity assessment (2010), O3 – PULS update discussed
- **Ågesta (PHWR, closed in 1974)**
  - Total activity assessment (2010)

Method

Prerequisites

- **Total operation according to plant specification:**
  - B1/2 – Actual operation time, other plants 40, 50 or 60y
- **Decay period at least one year:**
  - I.e. short-lived nuclides excluded
- **All operational waste removed:**
  - Some small remaining activity in waste systems assumed
- **No major system decontamination before decommissioning**
- **Only plant materials expected to exceed exemption levels are included**

Input to activity assessment

- **SAR – Activity data (recent updates performed for most plants)**
  - Including calculation models for activity inventories
- **Plant data:**
  - Dose rate measurements, gamma scans, reactor water activity, fuel failure history, steam moisture content
- **Component weights and surface areas in contact with process media broken down in source term "Idents"**
  - Ident – System or part of system with certain contamination level
- **Future operation data:**
  - Total operation time, planned modifications (e.g. power uprates), reference time for decommissioning

Source terms considered

- **Neutron induced activity in internals, RPV and biological shield (concrete and reinforcement)**
  - Neutron flux (MCNP), material compositions, neutron activation calculations (IndAct, FISPACT)
- **Activated corrosion products on system surfaces (“Crud”)**
  - Model CrudAct for BWR and PWR for primary system
  - Relative distribution between different systems based on dose rate and gamma scan measurements
- **Fission products and actinides from leaking fuel:**
  - SAR leakage models combined with plant data
  - Fuel dissolution results in:
    - Actinide incorporation in system oxides (long memory effect)
    - Tramp U on core → Noble gas daughters in offgas systems
- **Contamination of concrete from system leakage**

Nuclides considered in decommissioning studies

($T_{½}$ >≈ 1 y)

Nuclide	$T_{½}$	Main occurrence
H-3	12.33 y	Control rods (BWR), concrete
C-14	5.73 ky	Internals, waste
Cl-36	302.01 ky	Internals, concrete, waste
Ca-41	103.00 ky	Insulation, concrete
Mn54	312.5 d	Internals, RPV, crud
Fe-55	2.70 y	Internals, RPV, crud
Co-60	5.27 y	Internals, crud
Ni-59	74.95 ky	Internals, crud
Ni-63	100.04 y	Internals, crud
Sr-90	29.12 y	Waste, offgas systems
Nb-94	20.30 ky	Internals, RPV
Tc-99	212.86 ky	Internals, RPV, waste
Ag108m	418.00 y	Control rods (PWR), crud
Ag110m	249.9 d	Control rods (PWR), crud
Cd113m	14.09 y	Control rods (PWR)
Sb-125	2.73 y	Crud
I-129	15.69 My	Waste
Cs-134	2.06 y	Waste, concrete, insulation
Cs-135	2.30 My	Waste, offgas systems
Cs-137	30.00 y	Waste, offgas systems
Sm-151	88.73 y	Concrete
Eu-152	13.32 y	Concrete
Eu-154	8.60 y	Concrete
Eu-155	4.96 y	Concrete
Pu-238	87.70 y	Waste, crud
Pu-239	24.11 ky	Waste, crud
Pu-240	6.56 ky	Waste, crud
Pu-241	14.40 y	Waste, crud
Am-241	432.71 y	Waste, crud
Cm-244	18.10 y	Waste, crud

O2: Example of system idents:

211.1 – RPV –

Induced activity and crud

211.2 – RPV Insulation –

Only induced activity

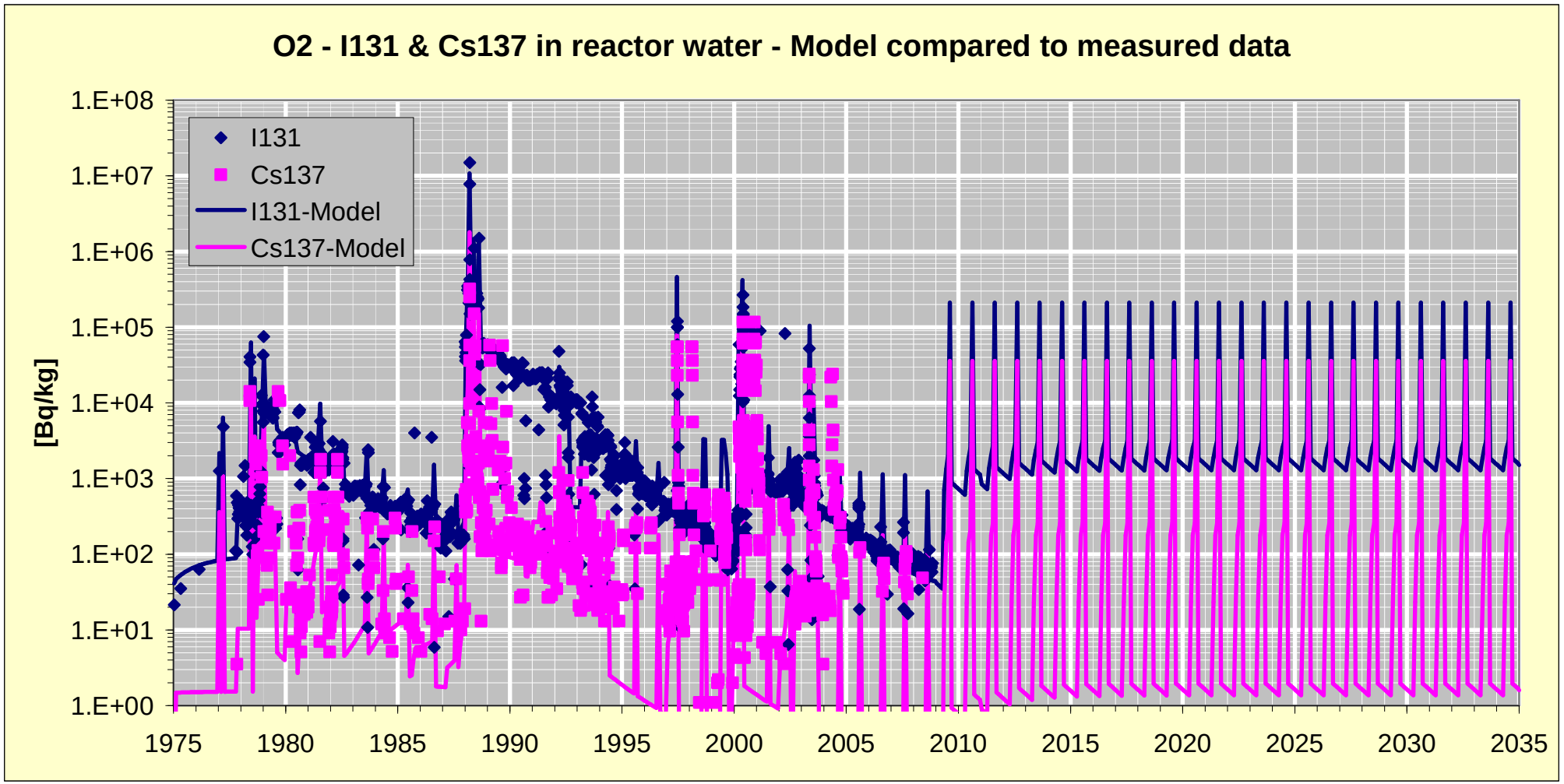
321.3 – Pipes in system 321 –

Only crud

Ident	O2.211.1		O2.211.2		O2.321.3	
Class [F/L/H]	H		H		H	
Rad [μSv/h]	3.2E+03		4.3E+01		6.5E+02	
Activity [Bq]	4.8E+13		8.5E+09		1.6E+11	
Activity [Bq/kg]	7.8E+07		1.7E+06		7.2E+06	
Unit	[Bq/m^2]	[Bq]	[Bq/m^2]	[Bq]	[Bq/m^2]	[Bq]
H-3				3.8E+05		
C-14	0	2.7E+09		1.9E+07		
Cl-36	0	2.1E+06		1.5E+07		
Ca-41				4.0E+08		
Mn54	4.9E+08	3.3E+12		2.9E+08	1.2E+07	4.2E+09
Fe-55	5.7E+09	3.4E+13		7.2E+09	1.4E+08	4.9E+10
Co-60	5.5E+09	5.5E+12		5.6E+08	1.4E+08	4.7E+10
Ni-59	5.1E+07	4.2E+10		2.4E+04	1.3E+06	4.4E+08
Ni-63	6.8E+09	5.1E+12		2.3E+06	1.7E+08	5.9E+10
Sr-90						
Nb-94	0	8.8E+07				
Tc-99	3.9E+03	5.1E+07			9.8E+01	3.4E+04
Sb-125	4.2E+07	2.4E+10			1.1E+06	3.6E+08
I-129						
Cs-134				1.0E+08		
Cs-135						
Cs-137						
Eu-152						
Eu-154						
Eu-155						
Pu-238	1.0E+05	5.7E+07			2.5E+03	8.8E+05
Pu-239	9.0E+03	5.1E+06			2.3E+02	7.8E+04
Pu-240	1.2E+04	6.5E+06			2.9E+02	1.0E+05
Pu-241	3.6E+06	2.1E+09			9.1E+04	3.1E+07
Am-241	5.2E+03	2.9E+06			1.3E+02	4.5E+04
Cm-244	1.6E+05	8.9E+07			3.9E+03	1.4E+06
	Source	**Factor**	**Source**	**Factor**	**Source**	**Factor**
Surface	Crud_321	2	0	0	Crud_321	0.05
Volume	I_211_1		I_211_2		0	
Area [m^2]	563		0		346	
Weight [kg]	620000		5000		22395	
[μSv/h per Bq/kg]	3.0E-04		3.0E-04		3.0E-04	
Nuclide	Co60		Co60		Co60	

Example of validation data:

O2: Fuel leakage model compared to measured data



B1/2 – Activity removed from system decontaminations

ref.date	2007-11-01	2007-11-01	2007-11-01	2007-11-01
	B1/2008 [Bq]	B2/2007 [Bq]	B2/2002 [Bq]	TOTAL [Bq]
Co-60	1.33E+12	2.13E+12	7.55E+11	4.21E+12
Fe-55	6.72E+11	1.28E+12	6.69E+11	2.42E+12
Mn-54	8.01E+08	3.98E+10	7.91E+08	4.14E+10
Ni-59	1.68E+09	1.18E+09	1.63E+09	4.50E+09
Ni-63	2.13E+11	1.59E+11	2.13E+11	5.86E+11
Sb-125	2.30E+10	6.60E+10	2.44E+10	1.13E+11
Tc-99	8.44E+05	3.25E+05	4.48E+05	1.62E+06
Pu-238	3.41E+06	**4.69E+06**	**1.52E+07**	2.33E+07
Pu-239	4.13E+05	**5.44E+05**	**1.76E+06**	2.72E+06
Pu-240	6.75E+05	**8.89E+05**	**2.87E+06**	4.44E+06
Pu-241	1.07E+08	**1.83E+08**	**5.93E+08**	8.83E+08
Am-241	1.57E+06	**4.03E+05**	**1.30E+06**	3.28E+06
Cm-244	3.56E+06	**5.79E+06**	**1.87E+07**	2.81E+07

Memory effect of fuel dissolution in B2 in 1992 (about 5 g of Tramp U

B1 – Comparison between measured and calculated activity in RPV insulation and biological shield

	Caposil [Bq/kg]		Al sheet [Bq/kg]	
Nuclide	***Calculated***	***Measured***	***Calculated***	***Measured***
Co-60	3.3E5	2.4E5	8.4E4	6.3E4
Cs-134	1.4E5	4.2E4		
Mn-54	5.6E5	5.2E5	3.2E4	2.0E4
Zn-65			1.6E5	6.3E4

	Concrete [Bq/kg]		Reinforcement [Bq/kg]	
Nuclide	***Calculated***	***Measured***	***Calculated***	***Measured***
Co-60	7.6E5	3.0E5	2.7E7	6.2E6
Mn-54			1.3E7	5.3E6
Cs-134	9.0E4	5.5E4		
Eu-152	1.8E6	1.3E6		
Eu-154	1.6E5	1.2E5		

O2 – Activity summary

	Activity inventory [Bq]								
	Reactor building (R)					Turbine building (T)			O2
	Concrete	RPV Internals	Pool walls	System 3xx	Total	332, 341, 348, 552	4xx	Total	Grand total
H-3	4.7E+12	3.5E+14	0.0E+00	0.0E+00	**3.5E+14**	0.0E+00	0.0E+00	**0.0E+00**	**3.5E+14**
C-14	1.6E+09	4.6E+12	0.0E+00	1.5E+08	**4.6E+12**	1.3E+09	0.0E+00	**1.3E+09**	**4.6E+12**
Cl-36	4.9E+07	1.7E+09	0.0E+00	1.9E+05	**1.8E+09**	2.3E+04	0.0E+00	**2.3E+04**	**1.8E+09**
Ca-41	4.8E+09	4.0E+08	0.0E+00	0.0E+00	**5.2E+09**	0.0E+00	0.0E+00	**0.0E+00**	**5.2E+09**
Mn-54	4.6E+10	9.7E+14	1.4E+11	6.0E+11	**9.7E+14**	1.8E+09	5.7E+09	**7.5E+09**	**9.7E+14**
Fe-55	4.5E+12	2.9E+16	1.6E+12	3.5E+12	**2.9E+16**	6.0E+09	6.7E+10	**7.3E+10**	**2.9E+16**
Co-60	4.6E+11	4.3E+15	1.6E+12	7.5E+12	**4.3E+15**	2.3E+10	6.4E+10	**8.8E+10**	**4.3E+15**
Ni-59	1.2E+09	3.3E+13	1.5E+10	8.6E+10	**3.3E+13**	2.8E+08	6.1E+08	**8.9E+08**	**3.3E+13**
Ni-63	1.4E+11	4.0E+15	1.9E+12	1.0E+13	**4.0E+15**	3.2E+10	8.0E+10	**1.1E+11**	**4.0E+15**
Sr-90	4.7E+07	0.0E+00	0.0E+00	7.5E+09	**7.6E+09**	1.5E+10	0.0E+00	**1.5E+10**	**2.3E+10**
Nb-94	1.7E+07	5.0E+10	0.0E+00	4.7E+01	**5.0E+10**	7.4E+00	0.0E+00	**7.4E+00**	**5.0E+10**
Tc-99	7.4E+06	4.8E+10	1.1E+06	3.7E+08	**4.9E+10**	1.0E+07	4.6E+04	**1.1E+07**	**4.9E+10**
Sb-125	3.5E+08	1.0E+12	1.2E+10	3.8E+10	**1.1E+12**	7.2E+07	4.9E+08	**5.7E+08**	**1.1E+12**
I-129	3.3E+04	0.0E+00	0.0E+00	2.5E+06	**2.6E+06**	1.8E+06	0.0E+00	**1.8E+06**	**4.3E+06**
Cs-134	1.6E+10	1.0E+08	0.0E+00	9.9E+10	**1.1E+11**	1.4E+08	0.0E+00	**1.4E+08**	**1.2E+11**
Cs-135	1.4E+05	0.0E+00	0.0E+00	1.3E+07	**1.3E+07**	3.0E+06	0.0E+00	**3.0E+06**	**1.6E+07**
Cs-137	1.7E+10	0.0E+00	0.0E+00	1.3E+12	**1.3E+12**	6.0E+10	0.0E+00	**6.0E+10**	**1.4E+12**
Eu-152	3.3E+11	0.0E+00	0.0E+00	0.0E+00	**3.3E+11**	0.0E+00	0.0E+00	**0.0E+00**	**3.3E+11**
Eu-154	1.5E+10	0.0E+00	0.0E+00	2.1E+08	**1.5E+10**	2.8E+07	0.0E+00	**2.8E+07**	**1.5E+10**
Eu-155	6.7E+09	0.0E+00	0.0E+00	5.6E+07	**6.8E+09**	7.9E+06	0.0E+00	**7.9E+06**	**6.8E+09**
Pu-238	1.3E+05	4.1E+08	2.9E+07	2.8E+08	**7.2E+08**	4.3E+07	1.2E+06	**4.4E+07**	**7.6E+08**
Pu-239	3.5E+06	3.6E+07	2.6E+06	4.2E+07	**8.4E+07**	6.8E+06	1.1E+05	**6.9E+06**	**9.1E+07**
Pu-240	1.9E+04	4.6E+07	3.3E+06	5.3E+07	**1.0E+08**	8.6E+06	1.4E+05	**8.7E+06**	**1.1E+08**
Pu-241	1.9E+06	1.5E+10	1.0E+09	3.6E+09	**1.9E+10**	3.9E+08	4.3E+07	**4.4E+08**	**2.0E+10**
Am-241	8.0E+03	2.1E+07	1.5E+06	2.1E+07	**4.3E+07**	3.3E+06	6.1E+04	**3.4E+06**	**4.6E+07**
Cm-244	9.8E+04	6.3E+08	4.5E+07	1.8E+08	**8.6E+08**	2.2E+07	1.9E+06	**2.3E+07**	**8.8E+08**
Total	1.0E+13	3.8E+16	5.3E+12	2.3E+13	**3.8E+16**	1.4E+11	2.2E+11	**3.6E+11**	**3.8E+16**
Weight [kg]	**6.5E+05**	**7.8E+05**	**2.0E+05**	**5.4E+05**	2.2E+06	**3.8E+05**	**8.6E+05**	1.2E+06	3.4E+06

Uncertainties

- **Main activity in reactor internals:**
  - Estimated uncertainty ± a factor 2
- **Larger uncertainties in systems far from reactor:**
  - Typically one order of magnitude
  - May have large impact on which system parts that can be exempted, i.e. the total waste volume
  - Note, no system decontaminations have been assumed, i.e. waste volumes are likely to be reduced through decontamination campaigns

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