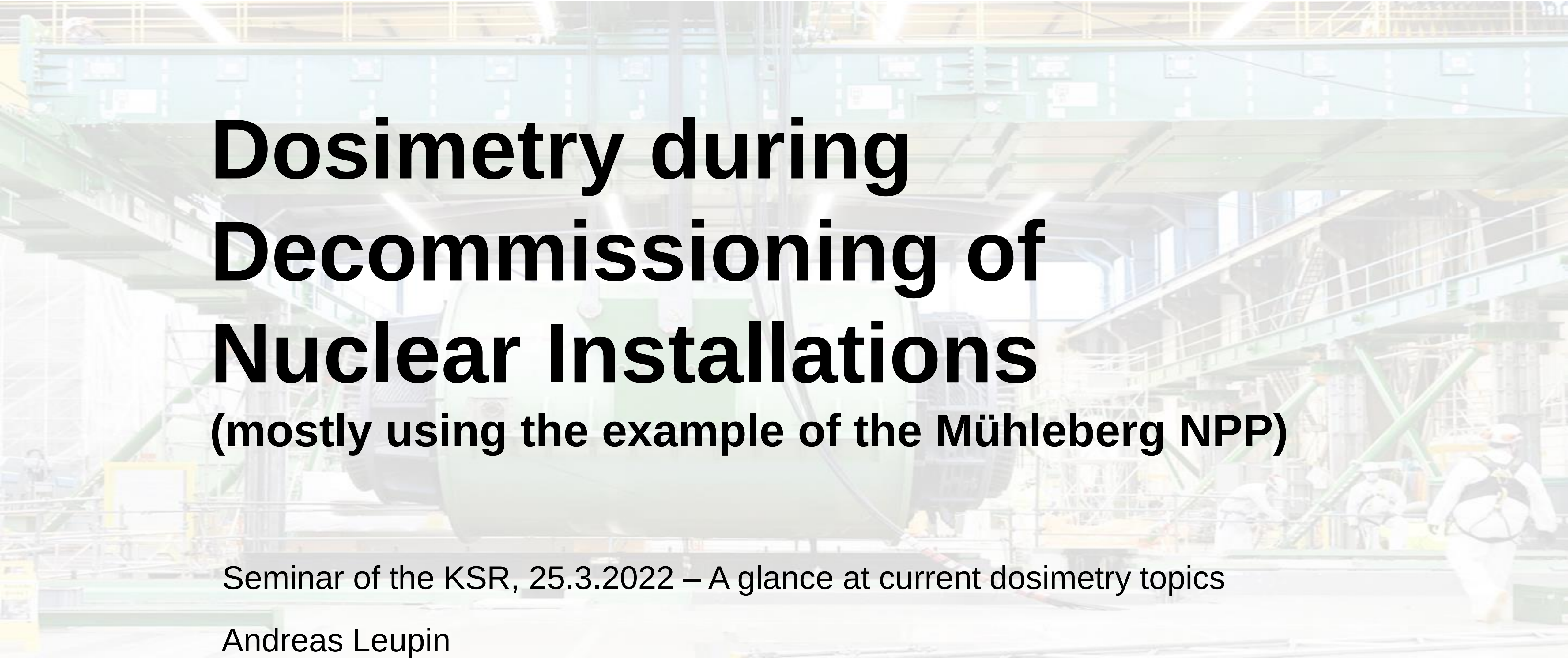

Dosimetry during Decommissioning of Nuclear Installations

(mostly using the example of the Mühleberg NPP)

Seminar of the KSR, 25.3.2022 – A glance at current dosimetry topics

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ENSI

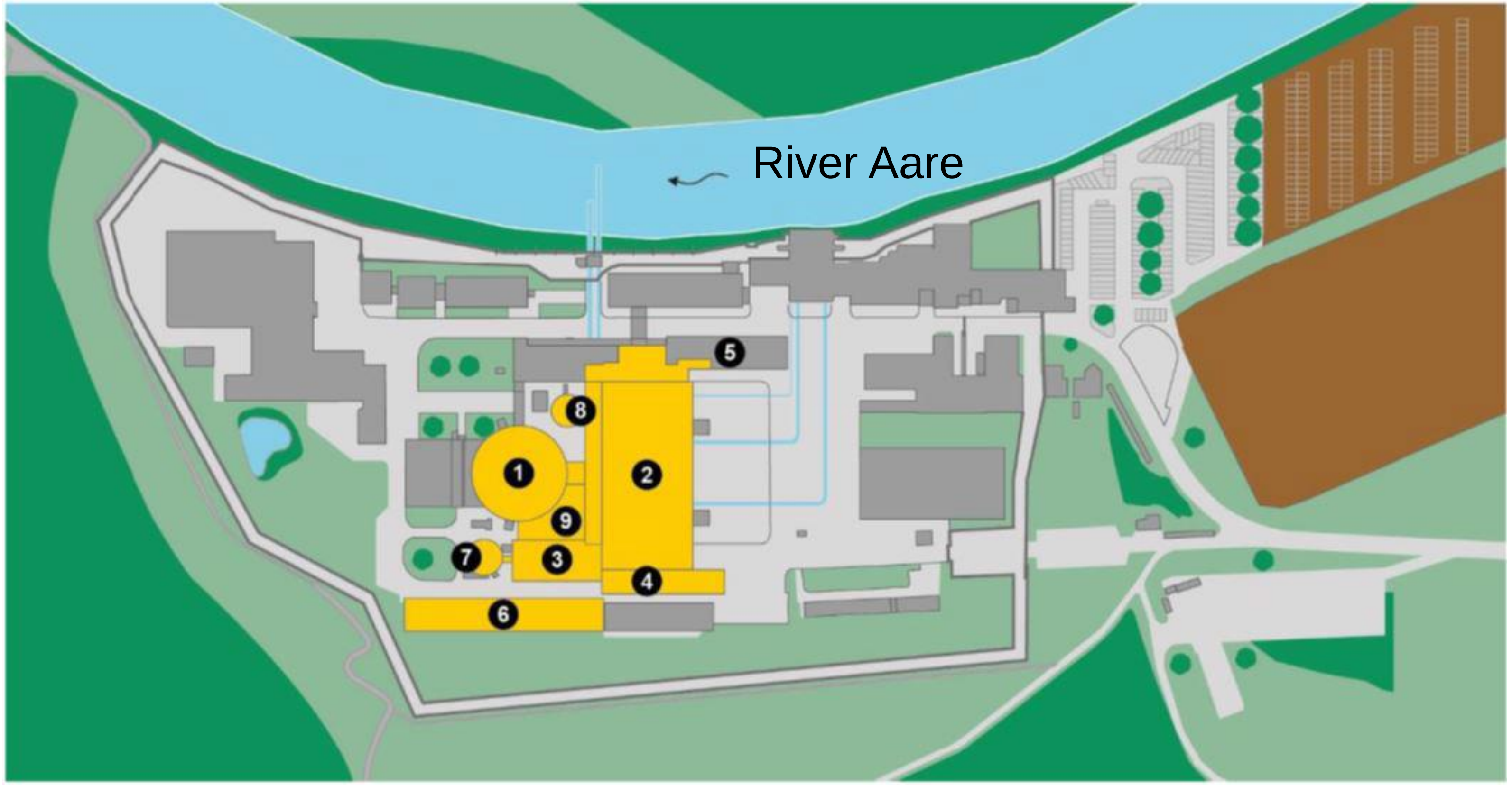
Background-Informations

- In October 2013, BKW Energy took the fundamental decision to cease power operations at the Mühleberg nuclear power plant (KKM) at the end of 2019 permanently and subsequently to decommission the KKM.
- Assuming a lifetime of 60 years, the next nuclear power plants would be decommissioned as follows: Beznau (2029/31), Gösgen (2040) and Leibstadt (2045)

Content of the Presentation

- The stages and phases of decommissioning and shutdown using the Mühleberg NPP (KKM) as an illustration
- Differences in Dosimetry between normal operation and decommissioning (also using the KKM as example)
  - Radiological characterisation of the plant (Operation vs. Decommissioning)
  - The importance of the radiological condition of the plant on the external and internal dosimetry of the staff
- Future decommissioning of other nuclear facilities in Switzerland
- Conclusions

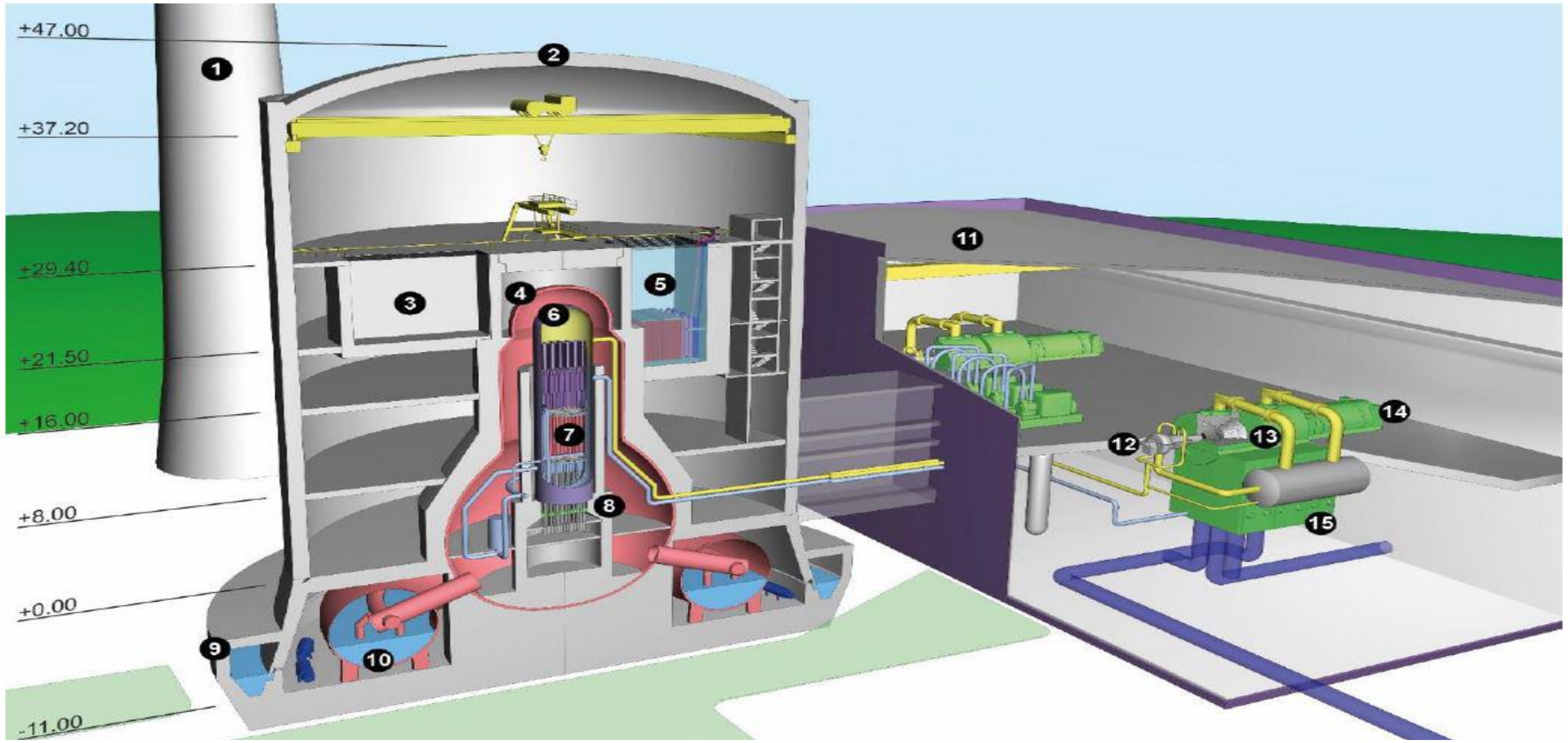
KKM as example: Overview of the facility (1)



Controlled Zone (State during Operation)

1	Reactor-Building (RG)	6	Interim storage facility for radioactive waste (ZL)
2	Engine House (MH)	7	Stack (KA)
3	Processing Building (AG)	8	Cold condensate tank (KB) incl. Cellar
4	Engine house extension south	9	Converter hall (UH), storage yard (LLS)
5	Parts of Operations building (BG)		

KKM as example: Overview of the facility (2)



1	Stack	9	Outer Torus	High exposure risk
2	Reactor Building (Secondary Containment)	10	Inner Torus	Moderate exposure risk
3	Fitting Pool	11	Engine House	
4	Drywell (Primary Containment)	12	High-pressure Turbine	
5	Fuel Storage Pool	13	Low-pressure Turbines	
6	Reactor Pressure Vessel	14	Generator	
7	Fuel Elements	15	Condensator	
8	Biological shield			

KKM as example: The stages of a Nuclear Power Plant

The lifetime of a nuclear power plant can be divided into four stages

- Planning (general licence),
- construction (construction licence),
- operation (operating licence) and
- Decommissioning (decommissioning order)

Each stage has its own "authorisation regime", this means it is based on its own authorisation or order, which comprehensively regulates the respective phase.

The Nuclear Energy Legislation assumes a seamless sequence of these authorisation regimes.

Internationally common decommissioning variants; Choice in the case of BKW/KKM and Justification

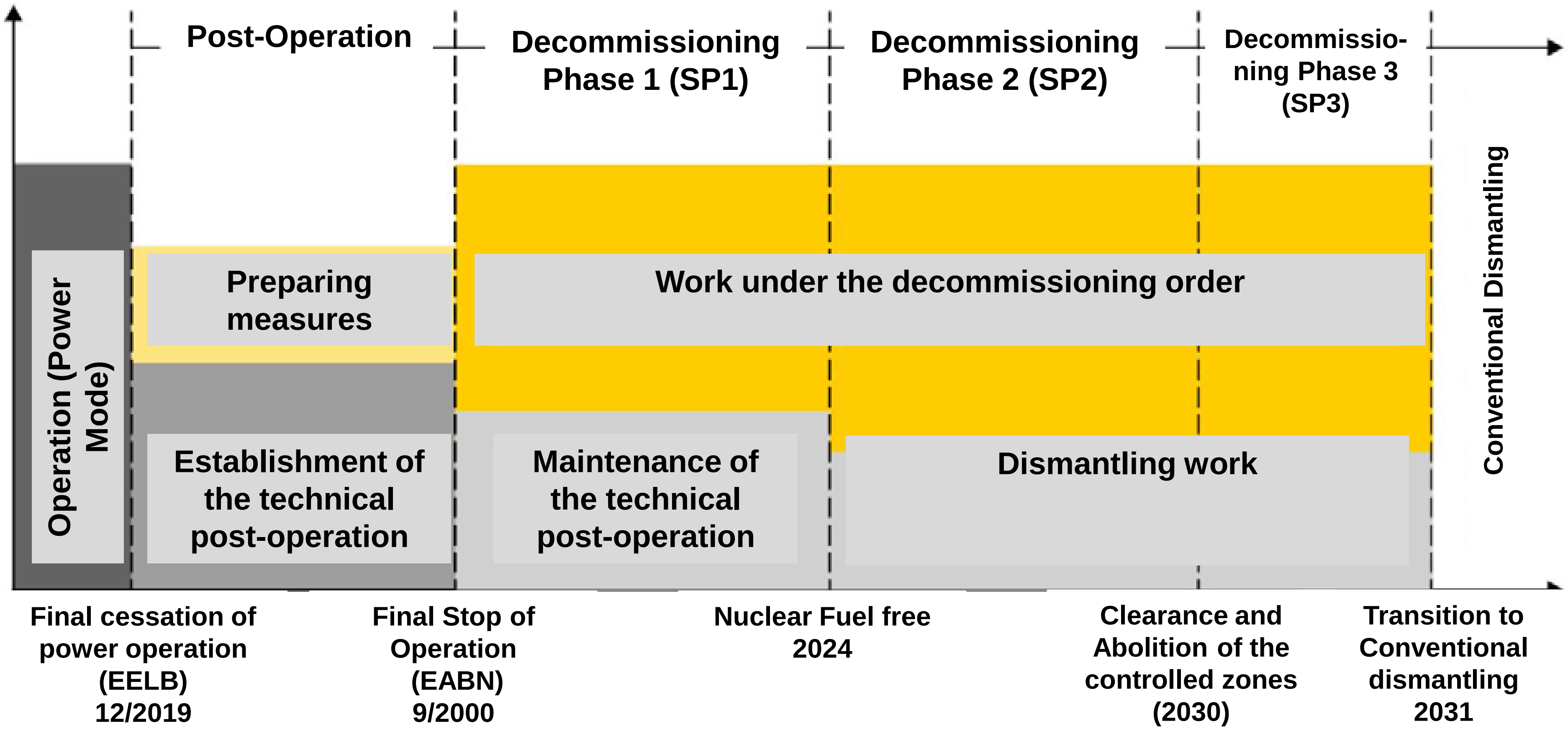
Internationally common decommissioning options:

- Direct Dismantling just after Cessation of the Power Operation (EELB)
- safe confinement for a longer period of time with time-delayed deconstruction

BKW/KKM chose the first decommissioning option because:

- Use of existing know-how and infrastructure
- Availability of experienced in-house personnel for planning and implementation
- Personnel perspectives through continuous employment opportunities
- Sufficient availability of nuclear service providers
- Solid calculability of costs due to timely start of dismantling
- High acceptance in society due to rapid removal of the plant

Phase concept and schedule for the decommissioning of KKM



Fundamental differences between the operating and decommissioning phases of a nuclear power plant

NPP during operation is characterised by

- A **continuous production** of new fission products, activation products and actinides;
- This results in an **increasing activity** inventory (long-lived nuclides) or an **equilibrium** situation (short-lived nuclides, e.g. Iodine);
- A reduction of the inventory only by decontamination actions or removal of spent fuel and radioactive waste
- The activity is confined mainly in fuel elements, in the reactor circuit and in reactor structures. Regarding dosimetry, the **external dose** (also from short-lived nuclides) is decisive during normal power operation.
- Work with "open" sources, contamination carry-over and releases into the plant during maintenance work and in the revision shutdown. **Internal Doses** (also from short lived nuclides) may also become important in this case.

NPP during decommissioning/dismantling

- **The activity inventory** in the plant **steadily decreases** (radioactive decay, disposal of the spent fuel and other radioactive waste during dismantling etc.)
- Work similar than during maintenance and revision shutdown – this means work with "open" sources, contamination carry-over and releases within the plant and, therefore, **higher importance of internal doses and long-lived nuclides.**

Radiological characterisation of the plant

The knowledge of the radiological situation in the planning of the dismanteling of a nuclear installation as well as continuously during the dismantling is absolutely crucial for the planning of the work, for radiation protection as well as for the dosimetry of the workers.

This requires continuous investigations, measurements and updates of the radiological status of the entire plant but also of specific systems to be dismanteled.

Radiological Characterisation of the Plant (KKM): Assessment from operational experience

- Radiological condition continuously monitored and documented during operation.
- Documentation contains all radiologically relevant data (e.g. activation, contamination as well as dose rate) of systems as well as of rooms in the plant (e.g. leakage etc.)
- Documentation entered also into the MIRAM database (maintained by NAGRA) for the characterisation of the radioactive waste foreseen for the future repository (Reference 2075).
- Many years of operation without significant fuel damage means very low level of contamination in the water-steam cycle due to fission products and Actinides and, therefore, a favorable radiological situation at the end of operation;
- Radiological Situation at end of operation and data from MIRAM allows the estimation of the radiological situation in the plant until 2075 (see the following considerations).

- But, since the radiological plant status changes during decommissioning, BKW continuously has to update the documentation of the radiological plant status throughout decommissioning.

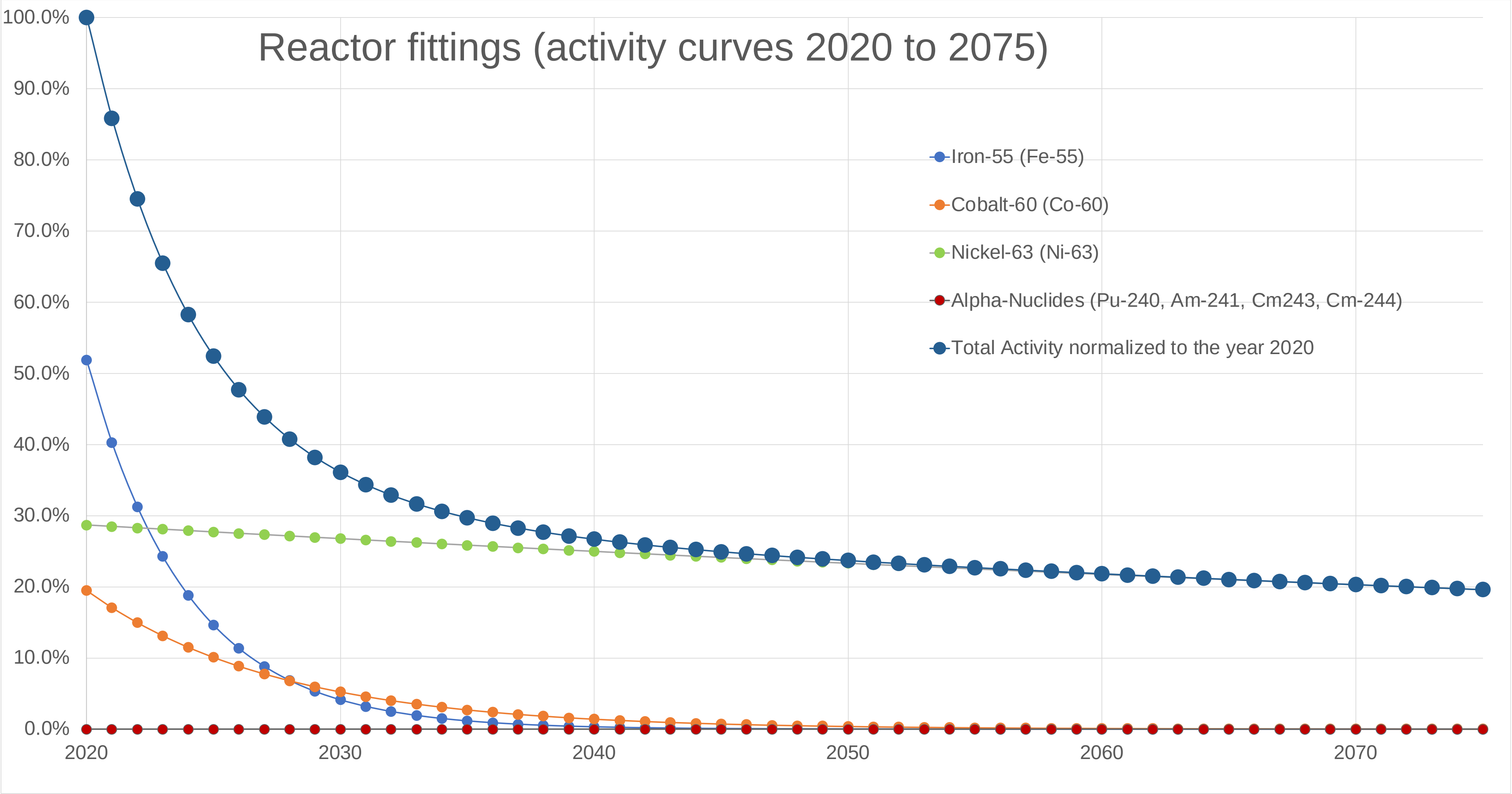
Key Nuclides relevant for external and internal Dosimetry during Operation and Decommissioning (1)

Nuclide	Type of Radiation	Half-Life	h_{10} [mSv/h/GBq]	e_{inh} [Sv/Bq]	e_{ing} [Sv/Bq]	Relevant during Operation; Post-operation; SP1; SP2; Long-Term () dosimetric relevance limited				
Fission Products:										
• Noble Gases	β/γ	hrs to days	0.264 (Kr-88)	-	-	(O)				
• Kr-85	β	10.76 a	0.001	-	-		(P)	(SP1)		
• Sr-90	β	28.79 a	-	**7.7E-8**	2.8E-8	(O)	(P)	(SP1)	(SP2)	L
• I-131	β/γ	8.021 d	**0.062**	**1.1E-8**	2.2E-8	O	(P)			
• Cs-134	β/γ	2.065 a	**0.236**	9.6E-9	1.9E-8	O	P	SP1	(SP2)	
• Cs-137	β/γ	30.17 a	**0.092**	6.7E-9	1.3E-8	O	P	SP1	SP2	L
Activation Products in Structural Materials:										
• Fe-55	ec	2.737 a	-	9.2E-10	3.3E-10	(O)	(P)	(SP1)	(SP2)	
• Co-58	β/γ	70.86 d	**0.147**	1.7E-9	7.4E-10	O	P	(SP1)		
• **Co-60**	β/γ	5.271 a	**0.366**	**1.7E-8**	3.4e-9	O	P	SP1	SP2	(L)
• Ni-63	β	100.1 a	-	5.2E-10	1.5E-10	(O)	(P)	(SP1)	(SP2)	L
• Ba-133	ec/γ	10.52 a	**0.085**	1.8E-9	1.0E-9	(O)	(P)	SP1	SP2	L
• Eu-152	β/γ	13.54 a	**0.179**	**2.7E-8**	1.4E-9	(O)	(P)	SP1	SP2	L

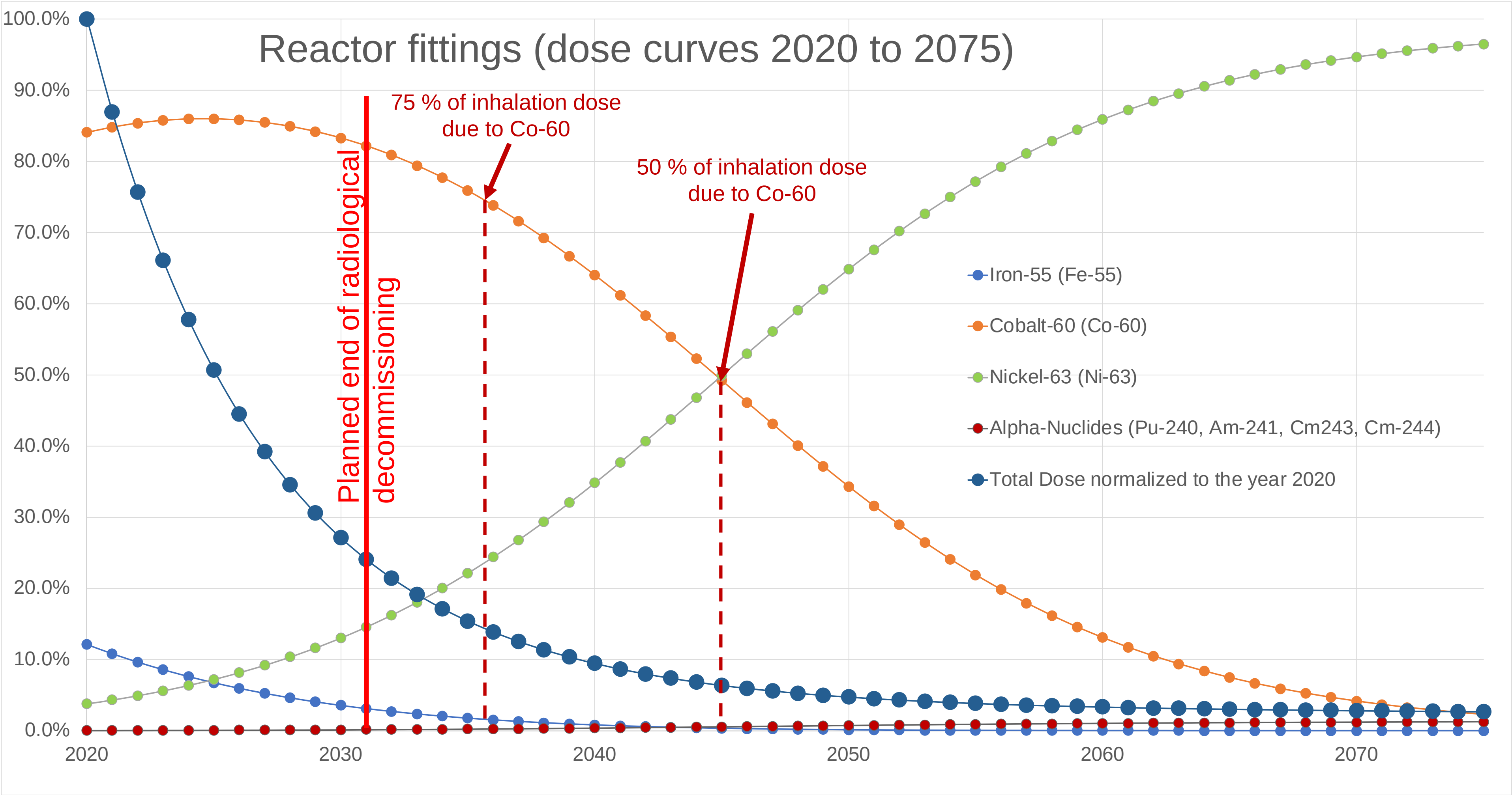
Key Nuclides relevant for Dosimetry during Operation and Decommissioning (2)

Nuclide	Type of Radiation	Half-Life	h_{10} [mSv/h/GBq]	e_{inh} [Sv/Bq]	e_{ing} [Sv/Bq]	Relevant during **O**peration; **P**ost-operation; **SP1**; **SP2**; **L**ong-Term				
Uraniums and Actinides (Transuraniums) in the fuel (mostly alpha-emitters, irrelevant for external dose):										
• U-235	α/γ	7.04E8 a	0.028	6.1E-6	4.6E-8	**O**	**P**	**SP1**	**SP2**	**L**
• U-238	α	4.47E9 a	0.002	5.7E-6	4.4E-8	**O**	**P**	**SP1**	**SP2**	**L**
• Pu-238	**α**	87.7 a	0.002	**3.0E-5**	2.3E-7	**O**	**P**	**SP1**	**SP2**	**L**
• Pu-239	**α**	2.41E4 a	0.001	**3.2E-5**	2.5E-7	**O**	**P**	**SP1**	**SP2**	**L**
• Pu-240	**α**	6.56E3 a	0.002	**3.2E-5**	2.5E-7	**O**	**P**	**SP1**	**SP2**	**L**
• Pu-241	β/(α)	14.35 a	-	5.8E-7	4.7E-9	**O**	**P**	**SP1**	**SP2**	**L**
• Np-239	β/γ	2.36 d	0.039	1.1E-9	8.0E-10	**O**				
• Am-241	**α/γ**	432.2 a	0.019	**2.7E-5**	2.0E-7	**O**	**P**	**SP1**	**SP2**	**L**
• Am-242m	β	141 a	0.006	**2.4E-5**	1.9E-7	**O**	**P**	**SP1**	**SP2**	**L**
• Cm-242	α	162.8 d	0.002	3.7E-6	1.2E-8	**O**	**P**	**SP1**	**SP2**	**L**
• Cm-243	**α**/γ	29.1 a	0.033	**2.0E-5**	1.5E-7	**O**	**P**	**SP1**	**SP2**	**L**
• Cm-244	**α**	18.1 a	0.002	**1.7E-5**	1.2E-7	**O**	**P**	**SP1**	**SP2**	**L**

Radiological characterisation, Reactor fittings (KKM): Activity curves (based on MIRAM, Reference 2075)



Radiological characterisation, Reactor fittings (KKM): Inhalation dose curves (Based on MIRAM, Reference: 2075)



Inhalation-Dose: Ratio between Beta/Gamma- to Alpha-Activity before the Cessation of Operation

Reactor water before annual shutdown:

- 2015: 500’000 to 1
- 2016: 200’000 to 1
- 2017: appr. 500’000 to 1

Reactor water during the annual shutdown:

2015: 150’000 to 1

2016: 100’000 to 1

RPV-lid (Scratch test)

- 2015: 73’500 to 1
- 2016: 4600 to 1

Reactor fittings

2019: 360 to 1

2021: 410 to 1

Drywell-Isolation valve (exposed to live steam)

- 2015: 18’000 to 1
- 2016: 12’000 to 1

Critical Ratio: $DF_{inh}(\alpha)/DF_{inh}$(Co-60): ca. 2000

Hotwell A – Floor

- 2016: 23’000 to 1

During operation, all measured Beta/Gamma to Alpha Activity ratios were in a range, in which it may be assumed, that the Gamma-radiation is the dominant contribution to the inhalation dose.

Inhalation Dose: Preservation of Evidence for Ni-63 before the cessation of operation

- Within the scope of preservation of evidence, the wastewater of the KKM is examined for Ni-63 in addition to the usual nuclides (gamma-, alpha-emitters, Sr-89/90) during the quarterly comparative sampling of ENSI. In initial measurements, no Ni-63 could be detected in the wastewater (LOD approx. 10 Bq/l). An improvement of the detection limit to approx. 1 Bq/l is planned.
- In collaboration between PSI, FOPH and ENSI the environment of KKM has been examined for special nuclides (alpha-emitters, Fe-55, Ni-63) in addition to the normal environmental monitoring program before the cessation of operation of KKM. Also here, no Ni-63 could be detected above limit of detection.

The respective Report "ERGÄNZUNGSPROGRAMM «NULLPEGELMESSUNG RÜCKBAU KERNKRAFTWERK MÜHLEBERG (KKM) 2017-2019» has been published on the Websites of FOPH and ENSI https://www.ensi.ch/de/wp-content/uploads/sites/2/2021/04/Nullpegelmessung_Rueckbau_KKM_2017_2019.pdf

Dosimetry during Operation and Decommissioning (exemplary for Mühleberg)

KKM continued to operate the following dosimetric facilities and procedures during the decommissioning activities (post-operational phase, SP1, SP2 and SP3)

- A recognized personal dosimetry service for external irradiation
- An additional personal dosimetry system using Active Personal Dosimeters (APD) für external Gamma irradiation
- A (recognized) incorporation measurement service (thorax and thyroid measurement station, probably will cease operation from SP2)
- Triage incorporation measuring stations able to detect Gamma-emitters
- Mobile air monitors with Alpha- and Beta-channels, which could be used as triage monitors for actinides
- In accident scenarios considered rare, internal alpha- and beta-dosimetry at a recognized incorporation measurement site (e.g. PSI) on a suspicion-oriented base.

Question:

Are these dosimetric facilities and organizational means still adequate during the decomissioning phases?

External Dosimetry (Operation and Decommissioning)

- The differences in external dosimetry (external gamma and neutron radiation) are marginal between normal operation and decommissioning.
- In both cases, the dose is determined with passive whole-body or extremity dosimeters (TLD, DIS, RPL) and, in special cases (handling of fuel elements), with neutron dosimeters (PDAC) from a recognized personal dosimetry service.
- In addition, active personal dosimeters (APD) are used in nuclear facilities during normal operation and dismantling for prompt monitoring and alerting as part of operational radiation protection and optimization.
- In decommissioning phase 2, when there is no more nuclear fuel in the plant, the use of neutron dosimeters will be obsolete.

Internal Dosimetry in Mühleberg for work involving an increased risk of inhalation

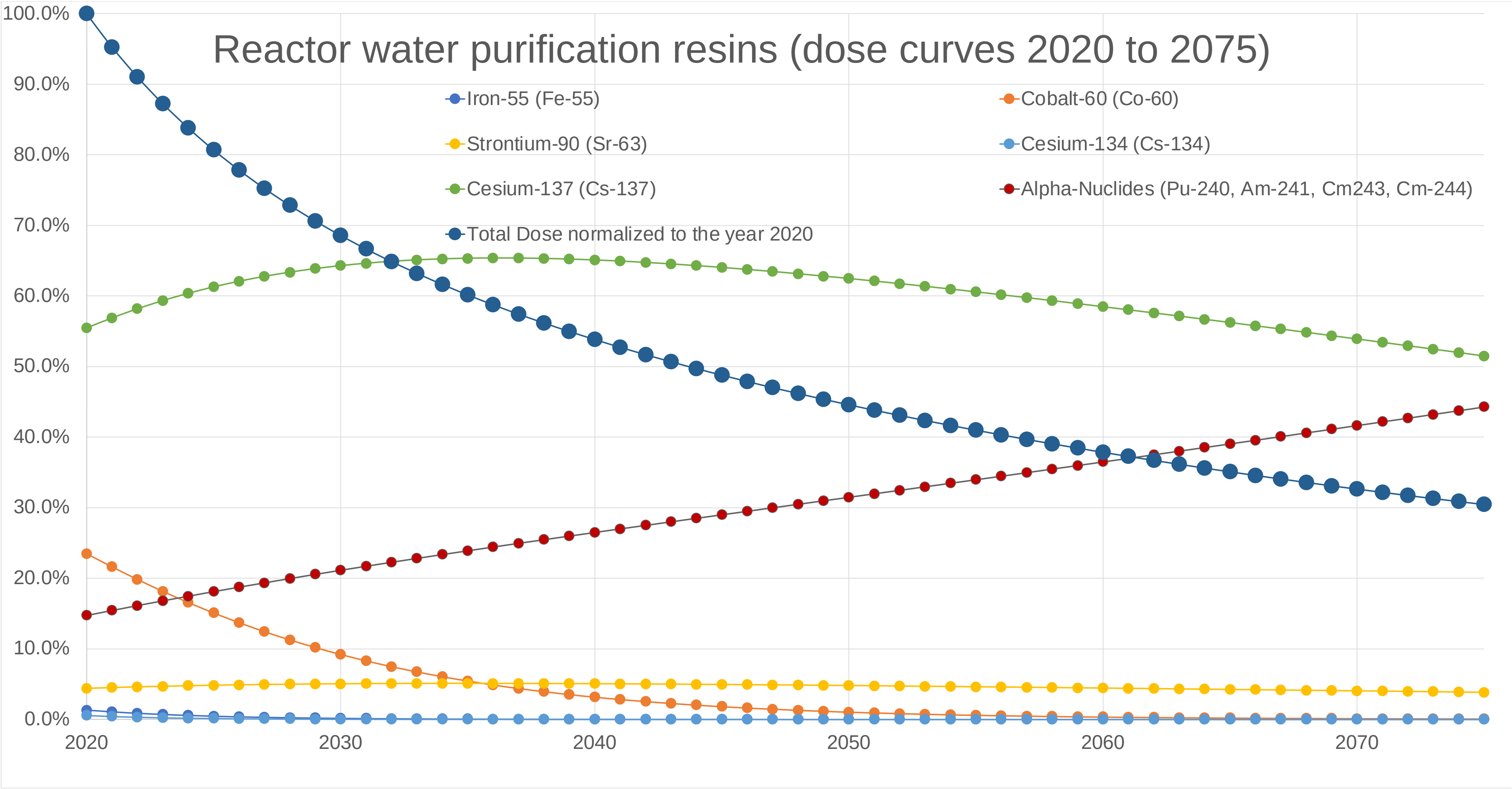
- All nuclear facilities monitor worker incorporation with regular triage measurements (Thorax Triage Monitors or Personal Contamination Monitors at the exit of the controlled areas)
- This is based on the assumption, that the relevant incorporation path is by inhalation and that the main dose is due to Gamma-radiators.
  As the radiological characterisation in the case Mühleberg shows, this is usually true for the nuclide-mixtures, which can be expected, for at least twenty years after cessation of operation.
- An incorporation dosimetry by a recognized personal dosimetry laboratory must be carried out
  - if the triage measurement threshold is exceeded or
  - In individual cases if the continuous radiological characterisation of the plant or of mobile air monitors shows significant proportions of alpha or pure beta emitters and there is a suspicion that radiation protection measures have failed.

Internal Dosimetry during Future Decommissioning of other Nuclear Facilities

The following lessons can be learned from the considerations for the Mühleberg nuclear power plant for the future dismantling of other nuclear power plants:

- Because the external dose is determined almost exclusively by gamma emitters, this part of the dosimetry is completely identical during operation and decommissioning
- Differences in dosimetry between operation and dismantling arise at most in the internal radiation exposure (i.e. determination of the dose from inhalation), depending on:
  - **The dismantling regime**: The later the decommissioning starts after the cessation of operation and the longer it lasts, the more important it is to consider usually long-lived pure beta- (Fe-55, Ni-63) and alpha emitters. However, dosimetry for pure beta and alpha emitters is significantly more complex, if there is no longer a gamma-emitting key-nuclide (e.g. Co-60) and, therefore, differs significantly from the dosimetry during operation;
  - **the number of fuel assemblies damaged during operation**: In the case of fuel element damages, actinides (usually pure alpha emitters) and fission products are released into the reactor water, which dominate the inhalation doses and also require an adjustment of the dosimetry during dismantling in case of a missing, gamma-emitting key-nuclide.

Radiological characterisation, Purification Resins (KKM): Inhalation dose curves (Based on MIRAM, Reference: 2075)



Conclusion concerning the Dosimetry during Decommissioning of Nuclear Installations

Mühleberg (actually in decommissioning)

In view of the favourable radiation protection situation at the end of operational lifetime in the Mühleberg power plant, the decreasing activity inventory in the plant and the protective measures taken for the staff in the event of critical work, the dosimetric means are suitable for ensuring dosimetry during dismantling in normal cases and in the event of accidents.

Other nuclear Installations (decommissioned in the future)

As in the case of the Mühleberg power plant done, the need for an adapted dosimetry during decommissioning must be clarified on the basis of a careful radiological characterisation after the end of operation and in the course of decommissioning, depending on the decommissioning regime and the fuel element damages that occurred during operation, in order to take into account the influence of beta and alpha emitters that are difficult to measure.

Für mehr Informationen besuchen Sie uns auf:

www.ensi.ch

www.ifsn.ch

http://twitter.com/#!/ENSI_CH

Radiological Characterisation of radioactive waste: Reactor fittings, Mühleberg, Reference year: 2075 (MIRAM-Database)

MIRAM 14 - Basisszenarium MIRAM 14 — **Referenzjahr: 2075**

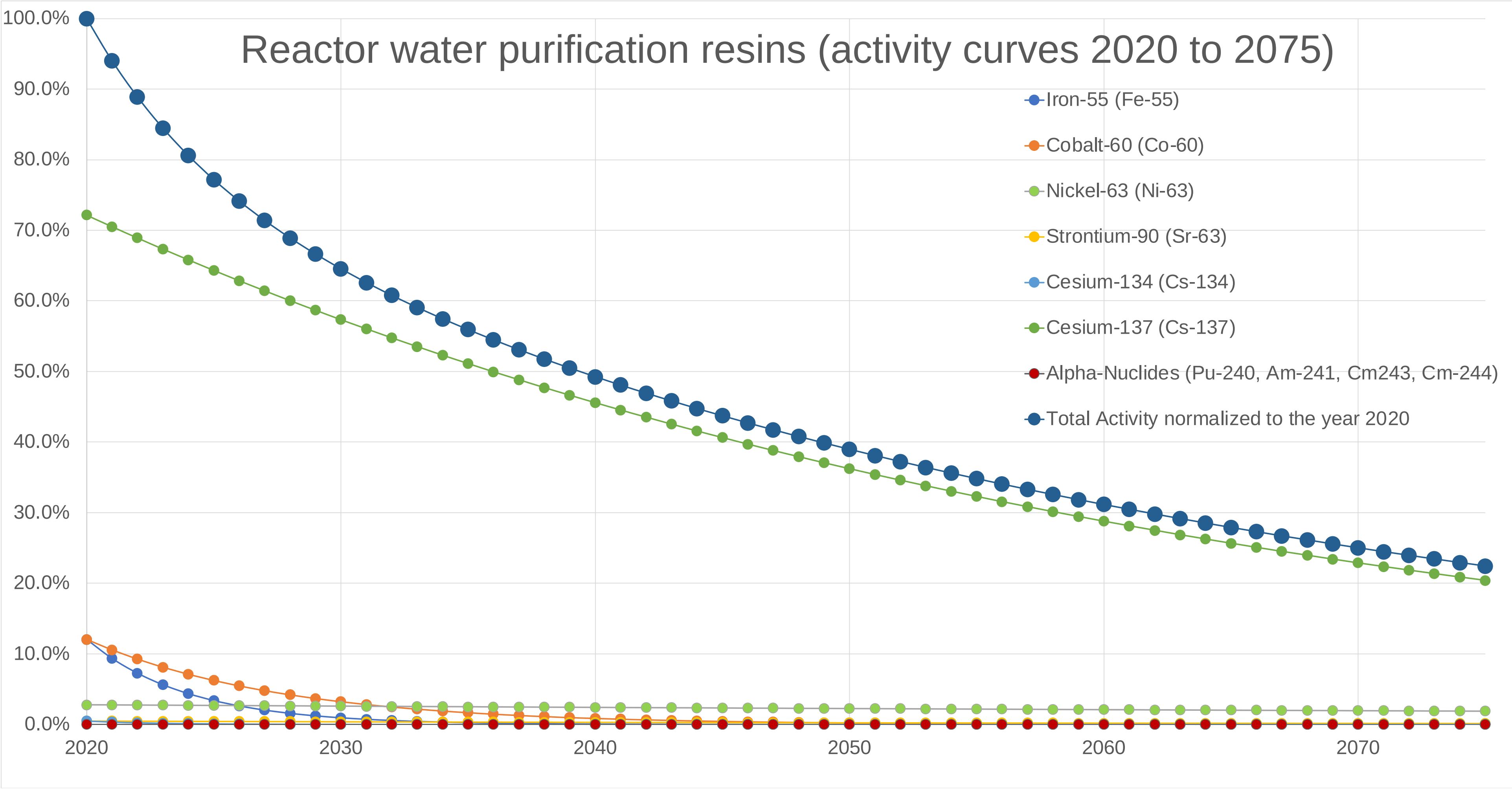
SA-M-ME-M2-SMA - Reaktoreinbauten in Mosaik-II

RADIOLOGISCHE KENNDATEN FÜR DAS REPRÄSENTATIVE GEBINDE

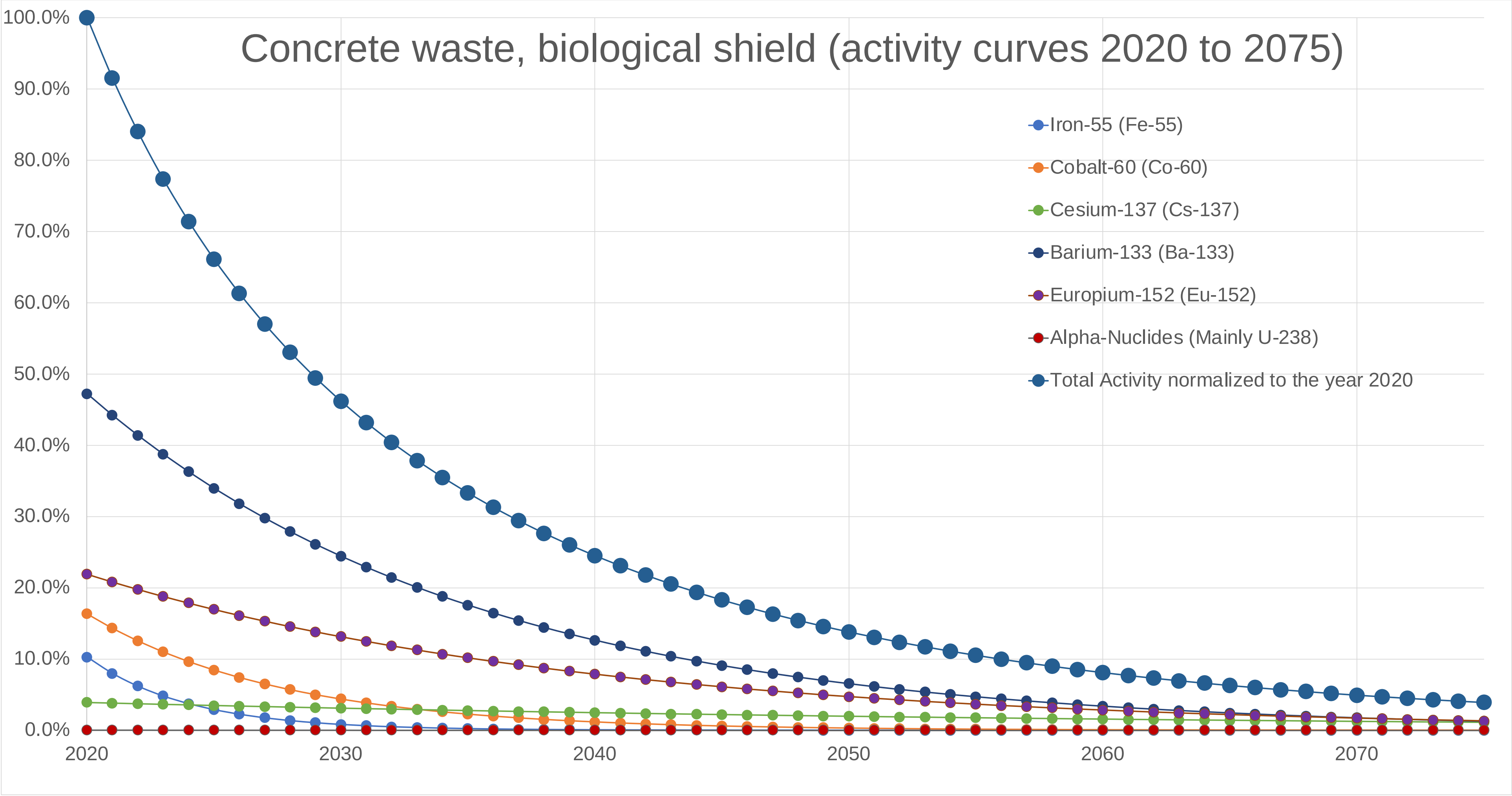
Nuklidinventar

Nuklid	*Aktivität [Bq]*		*Nuklid*	*Aktivität [Bq]*		*Nuklid*	*Aktivität [Bq]*		*Nuklid*	*Aktivität [Bq]*	
	Mittel	*Maximal*		*Mittel*	*Maximal*		*Mittel*	*Maximal*		*Mittel*	*Maximal*
H-3	8.5E+09	2.1E+10	Sn-121M	8.6E+04	1.4E+05	Pb-209	7.5E+02	1.9E+03	U-232	1.9E+05	5.1E+05
Be-10	4.7E+03	1.2E+04	Sn-126	1.4E+04	2.2E+04	Pb-211	1.1E+03	2.8E+03	U-233	1.0E+05	2.5E+05
C-14	4.7E+10	1.2E+11	Sb-125	1.5E+04	2.4E+04	Pb-212	2.0E+05	5.2E+05	U-234	1.3E+04	2.8E+04
Si-32	5.9E+02	1.6E+03	Sb-126	1.9E+03	3.1E+03	Bi-211	1.1E+03	2.8E+03	U-235	7.8E+03	1.2E+04
P-32	5.9E+02	1.6E+03	Sb-126M	1.4E+04	2.2E+04	Bi-212	2.0E+05	5.2E+05	U-235M	3.4E+05	6.3E+05
Cl-36	1.7E+09	4.4E+09	Te-125M	3.7E+03	5.9E+03	Bi-213	7.5E+02	1.9E+03	U-236	2.1E+02	3.4E+02
Ar-39	5.4E+07	1.4E+08	I-129	1.6E+01	2.6E+01	Po-211	3.0E+00	7.7E+00	U-237	2.0E+02	3.6E+02
K-40	5.3E+03	1.4E+04	Cs-134	2.7E+01	6.7E+01	Po-212	1.3E+05	3.3E+05	U-238	3.7E+03	6.0E+03
Ca-41	8.4E+08	2.2E+09	Cs-135	1.2E+04	3.0E+04	Po-213	7.4E+02	1.9E+03	Np-237	3.4E+02	5.6E+02
Fe-55	1.0E+08	2.6E+08	Cs-137	1.9E+07	4.3E+07	Po-215	1.1E+03	2.8E+03	Np-238	9.3E+01	2.2E+02
Co-60	3.1E+10	7.9E+10	Ba-133	6.0E+07	1.5E+08	Po-216	2.0E+05	5.2E+05	Np-239	6.4E+04	1.1E+05
Ni-59	5.1E+11	1.3E+12	Ba-137M	1.8E+07	4.0E+07	At-217	7.5E+02	1.9E+03	Pu-238	3.1E+06	6.1E+06
Ni-63	4.2E+13	1.1E+14	La-137	8.4E+06	2.2E+07	Rn-219	1.1E+03	2.8E+03	Pu-239	3.4E+05	6.3E+05
Se-79	1.0E+07	2.6E+07	Pm-145	8.9E+05	2.3E+06	Rn-220	2.0E+05	5.2E+05	Pu-240	7.0E+05	1.3E+06
Kr-81	3.4E+05	8.9E+05	Pm-147	3.5E+01	5.9E+01	Fr-221	7.5E+02	1.9E+03	Pu-241	8.1E+06	1.5E+07
Kr-85	1.1E+05	3.0E+05	Sm-151	4.0E+07	8.7E+07	Fr-223	1.5E+01	3.9E+01	Pu-242	2.3E+04	3.8E+04
Rb-87	1.7E+03	3.4E+03	Eu-152	1.7E+07	2.8E+07	Ra-223	1.1E+03	2.8E+03	Am-241	4.3E+06	8.3E+06
Sr-90	1.4E+07	3.2E+07	Eu-154	4.0E+07	1.0E+08	Ra-224	2.0E+05	5.2E+05	Am-242	1.9E+04	4.5E+04
Y-90	1.4E+07	3.2E+07	Eu-155	3.2E+05	8.3E+05	Ra-225	7.5E+02	1.9E+03	Am-242M	1.9E+04	4.5E+04
Zr-93	1.2E+05	2.7E+05	Tb-157	4.7E+06	1.2E+07	Ac-225	7.5E+02	1.9E+03	Am-243	6.4E+04	1.1E+05
Nb-92	6.1E+02	1.6E+03	Ho-166M	1.2E+08	3.2E+08	Ac-227	1.1E+03	2.8E+03	Cm-242	1.6E+04	3.7E+04
Nb-93M	5.0E+08	1.3E+09	Re-187	2.4E+03	6.2E+03	Th-227	1.1E+03	2.8E+03	Cm-243	9.1E+05	1.4E+06
Nb-94	1.3E+09	3.3E+09	Ir-192	2.3E+03	6.1E+03	Th-228	2.0E+05	5.2E+05	Cm-244	7.6E+05	1.4E+06
Mo-93	5.1E+08	1.3E+09	Ir-192M	2.3E+03	6.1E+03	Th-229	7.5E+02	1.9E+03	Cm-245	3.1E+02	6.1E+02
Tc-99	5.4E+07	1.4E+08	Pt-193	9.2E+05	2.4E+06	Th-230	5.7E+00	1.3E+01	Cm-246	2.1E+02	4.9E+02
Pd-107	3.6E+01	7.7E+01	Tl-204	2.5E+06	6.5E+06	Th-231	7.8E+03	1.2E+04			
Ag-108	4.4E+07	1.1E+08	Tl-207	1.1E+03	2.8E+03	Th-234	3.7E+03	6.0E+03			
Ag-108M	5.1E+08	1.3E+09	Tl-208	7.2E+04	1.9E+05	Pa-231	1.2E+03	3.2E+03	Summe α	1.2E+07	2.3E+07
Cd-113M	1.4E+03	2.6E+03	Tl-209	1.6E+01	4.1E+01	Pa-233	3.4E+02	5.6E+02	Summe βγ	4.3E+13	1.1E+14
Sn-121	6.7E+04	1.1E+05	Pb-205	2.5E+03	6.5E+03	Pa-234	3.7E+03	6.0E+03	Total	4.3E+13	1.1E+14

Radiological characterisation, Purification Resins (KKM): Activity curves (based on MIRAM, Reference 2075)



Radiological characterisation, Concrete Waste (KKM): Activity curves (based on MIRAM, Reference 2075)



Radiological characterisation, Concrete Waste: Inhalation dose curves (Based on MIRAM, Reference: 2075)