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port2004@ijs.si
www.drustvo-js.si/port2004
+386 1 588 5247, fax +386 1 561 2276
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Determination of Source Term for Krško NPP Extended Fuel Cycle

Tomaž Nemec, Andreja Peršič
Slovenian Nuclear Safety Administration
Železna cesta 16, P.O.Box 5759, SI-1001 Ljubljana, Slovenia
tomaz.nemec@gov.si, andreja.persic@gov.si

Tomaž Žagar, Bojan Žefran
"Jožef Stefan" Institute
Jamova 39, SI-1000 Ljubljana, Slovenia
tomaz.zagar@ijs.si [*], bojan.zefran@ijs.si

ABSTRACT

The activity and composition of the potential radioactive releases (source term) is important in the decision making about off-site emergency measures in case of a release into environment. Power uprate of Krško NPP during modernization in 2000 as well as changing of the fuel type and the core design have influenced the source term value. In 2003 a project of "Jožef Stefan" Institute and Slovenian nuclear safety administration determined a plant-specific source term for new conditions of fuel type and burnup for extended fuel cycle. Calculations of activity and isotopic composition of the core have been performed with ORIGEN-ARP program. Results showed that the core activity for extended 15 months fuel cycle is slightly lower than for the 12 months cycles, mainly due to larger share of fresh fuel.

1 INTRODUCTION

In case of emergency at Krško NPP an emergency response organisation is formed at Slovenian nuclear safety administration (SNSA). Estimation of plant conditions and radioactive releases in case of fuel melting is performed by the Expert team for analysis of nuclear accident [1]. The Expert team is formed from members of SNSA, "Jožef Stefan" Institute and other Technical support organizations. Releases from damaged fuel depend mainly on the core temperature and subsequently on the fuel burnup and on the cooldown time after reactor shutdown. The activity and isotopic composition of the potential releases (source term) is important in decision making about off-site emergency measures in case of a radioactive release into environment. At present a conservative source term value derived from generic data [2] is used, but this value is considering only the end of cycle (EOL) conditions and does not allow evaluation of specific conditions.

Power uprate of Krško NPP during modernization in 2000 as well as changing of fuel type and core design have influenced the source term. Another important contribution was the cycle extension to 15 months in 2003. These effects have not been yet properly evaluated and taken into account in quantification of potential radioactive releases. Therefore, SNSA launched a project with "Jožef Stefan" Institute to determine a plant specific source term for

[*] Current temporary email address: tomaz.zagar@itu.fzk.de

new fuel type with higher enrichment and burnup for the core design of extended fuel cycles of Krško NPP. To evaluate the releases of an accident in different phases of fuel cycle, the source term values have been determined for beginning, middle and end of a fuel cycle [3].

2 CALCULATION METHODS

2.1 Origen-ARP program

Calculations of activity and isotopic composition of the core have been performed with ORIGEN-ARP program [4], which is used for calculation of isotopes generation, burnup and radioactive decay during irradiation in a reactor core. Beside the core activity calculations ORIGEN also enables determination of the quantities of individual isotopes (mass and activity), radiation source terms, as well as the decay heat generated by the fuel. For this project a new version of ORIGEN program was aquired, which employs new methods and multigroup nuclear data libraries, thus giving more realistic results. The libraries can be used for fuel enrichments from 1.5 to 5 wt % of U-235 and fuel burnups from 0 to 60,000 MWD/MTU. The program allows use of new source options and facilitates the fast definition of input data, automated display and plotting of spectral results. Calculation with ORIGEN is done separately for fission products, actinides and activation products.

2.2 Input data

Data to construct the input for ORIGEN calculations have been taken from the documentation on Krško NPP core design for individual fuel cycles, e.g. [5]. In Table 1 are presented input data for ORIGEN calculations for fuel cycles 18, 19 and 20. Core of cycle 20 is composed of fuel with different enrichments: 3.4 wt %, 4.75 wt % and 4.95 wt %. Since Krško NPP modernisation and power uprate in 2000 the reactor thermal power is 1994 MWt. Cycles 18 and 19 employ equilibrium 12-months core designs, while cycle 20 is a 15-months cycle leading to cycle 21, which shall be a 18-months cycle. Thus, in core design of transition cycle 20 a larger share of fresh fuel with higher enrichment was used.

Table 1: Input data for fuel cycles 18, 19 and 20

fuel cycle	18	19	20
average enrichment [wt %]	4.3	4.3	4.5165
initial mass of uranium [MTU]	49.360	49.236	49.149
cycle length [EFPD]	325	325	430
average power [MWt/MTU]	40.397	40.499	40.570
EOL burnup [MWD/MTU]	13,110	13,163	17,340
cumulative EOL burnup [MWD/MTU]	32,263	31,538	33,275

2.3 Fuel burnup calculations

Fuel burnup in the core was accumulated through several cycles so the total fuel activity is a sum of individual irradiations of a core region. During annual outages between the cycles a decay of fuel activity (cooldown) occured, so the duration of the outages had to be considered in calculation of fission products quantity decrease.

In burnup calculation two different approaches were used: the first one with averaging of the fuel characteristics (enrichment, burnup) over the entire core and the second one considering each core region separately and then deriving a sum total of the results for individual regions. The results obtained were identical in the range of data uncertainties. The averaging approach has the advantage of enabling fast recalculation of core activity with variation of irradiation or cooldown times, what is especially useful in source term recalculation during the course of an accident scenario. On the other hand, the regionwise approach is more useful for calculation of activities for new core designs, where only the data for the fresh fuel region have to be added to the precalculated results. In this way, by variation of characteristics of the new region, studies of source terms for future core designs can be performed.

2.4 Determination of core inventory

Since the aim of the project was to establish the core activity in case of an accident in the NPP, the results were calculated for different cooldown times after the chain reaction has been stopped. In an accident scenario, the fuel damage and eventual release into environment would only occur after a certain period of time following the reactor shutdown. This decay time has a considerable influence on short lived isotopes so that the core activity decreases fast. To calculate a realistic source term value it is very important to choose the correct decay time. To better evaluate the releases of an accident the source term values need to be determined at different phases of fuel cycle. The caluculations shall be performed at least for beginning, middle and end of a fuel cycle. However, if time allows during an accident scenario, it is also possible to calculate the source term values for each chosen combination of burnup and cooldown times.

3 RESULTS AND DISCUSSION

3.1 Core total activity

Results of ORIGEN calculations are presented in an output file, where activities are shown for over 1000 individual isotopes divided into three distinct groups: fission products, actinides and activation products. A sum of individual isotope activities gives the core total activity of a single group which is an overview useful for comparison of different fuel cycles. In Figure 1 the core total activity is presented for equilibrium 12-months long cycles 18 and 19 and the extended 15-months long cycle 20, which is a transition cycle.

Due to extended cycle length one would expect that the activity of cycle 20 would increase by about 32 %, but resulting activity is even slightly lower than those of 12-months cycles. In fact, burnup of cycle 20 is larger than for 12-months cycles, but the accumulated activity from the previous cycles is smaller due to a larger share of fresh fuel in the core design of this transition cycle. The combination of these two effects amounts to almost the same total core activity of 15-months and 12-months cycles.

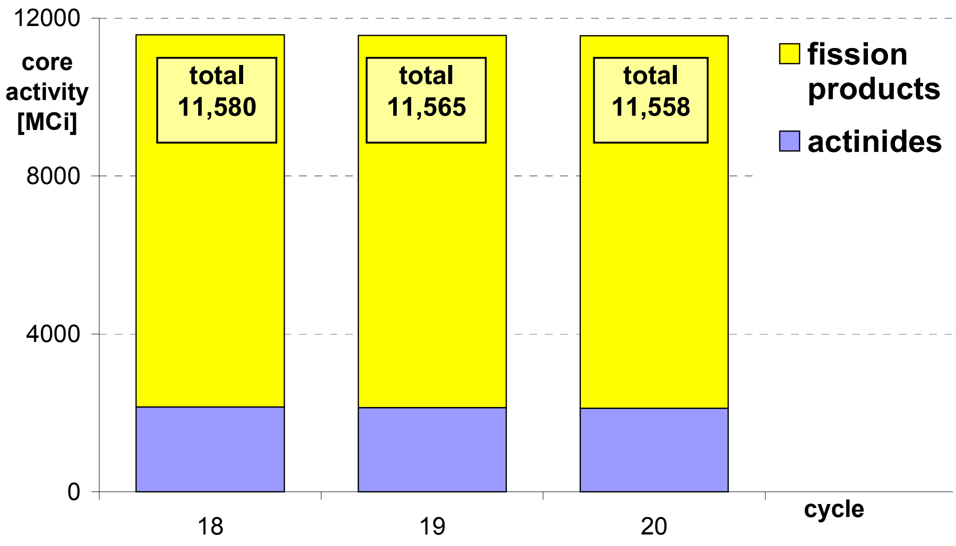

Figure 1: Core total activity† of fuel cycles 18, 19 and 20

3.2 Core isotopic composition for different cycle lengths

Among ORIGEN results we have selected 14 isotopes for comparison with the specific set of isotopes that is used in the manual for source term determination [1]. Activities for this set of isotopes are presented in Table 2 for each cycle and the values are compared with generic values from an IAEA TECDOC [2], which are currently used in the manual. These generic values are representative for inventory of fission products and activation products in a light water reactor core about 30 minutes after shutdown with an assumption of an equilibrium 18-months long fuel cycle. Generic data are normalized to a unit of reactor power (MWe) and have to be calculated for specific nuclear power plant.

Table 2: Comparison of core isotopic composition for cycles 18, 19 and 20

isotope	**generic values** [2]	**cycle 18**	**cycle 19**	**cycle 20**
	[MCi]	[MCi]	[MCi]	[MCi]
Kr-85m	16	13.73	13.84	13.85
Kr-87	31	27.59	27.82	27.85
Kr-88	45	38.35	38.68	38.72
Sr-89	62	53.44	53.88	53.96
Y-91	79	68.69	69.16	69.27
Mo-99	106	100.3	100.3	100.3
I-133	112	110.2	110.3	110.2
I-134	125	122.3	122.5	122.4
I-135	99	104.9	104.9	104.9
Xe-133	112.2	105.8	105.8	105.9
Xe-138	112.2	94.30	94.49	94.50
Ba-140	106	97.76	97.91	97.90
La-140	106	103.5	103.7	103.5
Np-239	1080	1027	1020	1010

† Units of MCi are used because of very high activity of the core. To convert units consider 1 MCi = $37 \cdot 10^{15}$ Bq.

Contents of individual isotopes are similar for different cycles. Comparison with generic values shows that the calculated values are similar to the generic ones but they remain up to 20 % below the currently used conservative source term values. With further extension of burnups in transitional 18-months long fuel cycle 21 and then in equilibrium 18-months long cycles the core inventory shall increase over the generic values. At present conditions the values for I-135 are already exceeded by 6 %. These discrepancies show that it is necessary to replace currently used generic data with plant specific values that should be updated for every specific fuel cycle. Calculated values of core inventory shall be included in the next revision of the manual.

3.3 Decay of core activity at different decay times

Results of core activity calculations depend on the chosen cooldown time. Two different cooldown times were selected: 1 year and 1 hour after reactor shutdown. Long decay time are suitable for exact modelling of the isotopes with half-lives in the range of days to years while short lived isotopes (half-lives below few minutes) are neglected. On the other hand, cooldown time of 1 hour is suitable for high activity isotopes with short half-lives while less active long lived isotopes are shadowed and with values below the threshold of 0.5 ‰ (promile) they are not presented in the output. Such results can not be correctly extrapolated to longer decay times.

3.4 Activation of fuel cladding

Since 1997 fuel with a different cladding material (ZIRLO) was introduced in Krško NPP. The ZIRLO cladding composition is notable for addition of Niobium, which improves its corrosion resistance. Analysis of alloys Zircaloy-4 and ZIRLO used for fuel cladding was performed using input data for material composition presented in Table 3. Analysis accounted for 258.8 kg of cladding material per 1MTU fuel and activation was calculated during 3 irradiation cycles considering also 2 cooldown periods during the outages.

Table 3: Composition of Zircaloy-4 and ZIRLO cladding materials.

element	**Zircaloy-4**		**ZIRLO**	
	[wt %]	[g]	[wt %]	[g]
Sn	1.20-1.45	14.5	0.90-1.10	11.0
Fe	0.18-0.24	2.4	0.08-0.12	1.2
Cr	0.07-0.13	1.3	0	0
Nb	0	0	0.8-1.2	12.0
Zr	rest	981.8	rest	975.8

Results of the study of fuel cladding activation are presented in Figure 2. The activity of ZIRLO cladding is slightly lower (2 %) than the Zircaloy-4 activity. However, when these activities are compared to fuel activities in Figure 1 it can be seen that cladding activities are 10,000 times smaller. In determination of source term the activity of fuel cladding is only a negligible contribution to the total source term of the reactor core.

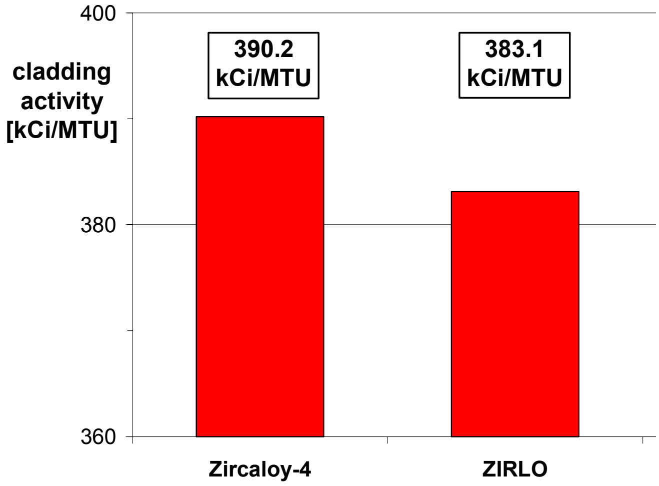

Figure 2: Activity of Zircaloy-4 and ZIRLO cladding materials

4 CONCLUSIONS

In the paper the results of the project of SNSA and "Jožef Stefan" Institute are presented. The studies evaluated the extension of fuel cycle at Krško NPP where the effects of increased fuel enrichment and higher burnups were considered. Against the expectations the resulting core total activity did not increase with cycle extension what can be attributed to the core design with larger share of fresh fuel. Higher cycle burnup and lower accumulated burnup of previous cycles resulted in even smaller activity than the 12-months cycles. A study of fuel cladding composition has been performed and showed that ZIRLO cladding activity is lower than Zircaloy activity.

Calculated values were compared also with generic data for source term estimation. Discrepancies between the two sets of values show that it is necessary to replace the currently used generic data with plant specific ones, which should also be updated for every fuel cycle to take into account its characteristics. When the data on new NEK core designs will be available, calculations will be performed also for the 18 months fuel cycles.

ORIGEN can also be used for calculations of decay heat and activity of high level radioactive waste what is important for storage and transportation of spent fuel as well as for reprocessing of spent fuel and transmuttation of actinides. Using ORIGEN for radiation protection purposes (dose rate estimate, shielding) is also possible by determination of gamma emittors between the fission products.

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