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DAVOR GRGIĆ davor.grgic@fer.hr

SINIŠA ŠADEK sinisa.sadek@fer.hr

VESNA BENČIK vesna.bencik@fer.hr

University of Zagreb Faculty of Electrical Engineering and Computing

DAMIR KONJAREK damir.konjarek@enconet.hr

Enconet d.o.o.

DECAY HEAT CALCULATION FOR SPENT FUEL POOL APPLICATION

SUMMARY

The automatic procedure was developed for fuel assembly decay heat calculation based on PARCS 3D burnup calculation for fuel cycle depletion, and ORIGEN 2.1 calculation during both depletion and fuel cooling. Using appropriate pre-processor and post-processor codes it is possible to calculate fuel assembly decay heat loads for all fuel assemblies discharged from reactor. Simple graphical application is then used to distribute fuel assemblies within fuel pool and to calculate any fuel assembly, SFP rack, or whole pool heat load at arbitrary time. The application can be used for overview of fuel assembly burnups, cooling times or decay heats. Based on given date it is possible to calculate whole pool heat load and time to boiling or time to assembly uncover using simple mass and energy balances. Calculated heat loads can be input to more detailed thermal-hydraulics calculations of spent fuel pool. The demonstration calculation was performed for NPP Krsko spent fuel pool.

Key words: burnup calculation, decay heat, ORIGEN, PARCS, spent fuel pool

1. INTRODUCTION

It was always important to have fast and accurate decay heat prediction, both in the core and in Spent Fuel Pool (SFP), but after accident in NPP Fukushima that is even more important. Calculation procedures are used based on existing well known computer codes, developed pre and post processors and some simple additional heat balance modules to calculate decay heat in reactor, or in SFP, both for selected assemblies of whole inventory. For decay heat calculation it is possible to use detailed ORIGEN 2.1 [1], [2] based calculation or fast calculation based on implementation of ANS Decay Heat Standard [3]. Calculated heat sources can be used for fast checking of core of SFP heat-up or as input in more complicated thermal hydraulics calculations.

2. ORIGEN 2.1 CALCULATION

ORIGEN 2.1 is old well known code able to calculate radioactive inventory and decay heat of nuclear fuel for selected depletion scheme and for prepared cross section and decay libraries. It is possible to use its newer versions distributed as part of SCALE package, but old version is easier to use, faster, and it is still able to give reliable results for scoping purposes. Most of the heat input in SFP is coming from last discharged spent fuel and it is more important to have accurate calculation for last depletion cycle. It is especially important if we have, due to some reason, to stop the plant and discharge the fuel to spent fuel pool. The same is always true for decay heat produced within reactor core during shutdown period.

In order to provide accurate burnup information needed for ORIGEN 2.1 calculations on fuel assembly bases, we used 3D multi cycle depletion capability from PARCS code [4]. As result of an additional postprocessing of PARCS calculation 2D distribution of fuel assembly burnups are produced for each internal PARCS depletion step. Using developed ORIGEN preprocessing code that and other information are used to prepare ORIGEN input for depletion of each fuel assembly in the core or in the spent fuel pool. As part of preprocessing time vector with decay time points is prepared and converted to ORIGEN DEC statements. It is possible to select calculation for any available fuel assembly or for all available of assemblies.

The scheme is valid not just for last depletion cycle, but for any past cycle for which necessary data are prepared. In Figure 1 burnup distributions are shown for cycle burnups 150 MWd/tU and 19500 MWd/tU, for NEK Cycle 26 [5]. Corresponding burnup increment to neighbouring cycle burnup point used in PARCS depletion is show in Figure 2. Equation (1) is then used by preprocessor to calculate Fuel Assembly (FA) power needed for ORIGEN IRP commands. The formula is based on information on FA burnup increment, FA high metal mass and time spent for that depletion step. ORIGEN postprocessor is then used to retrieve decay heat data for input time points.

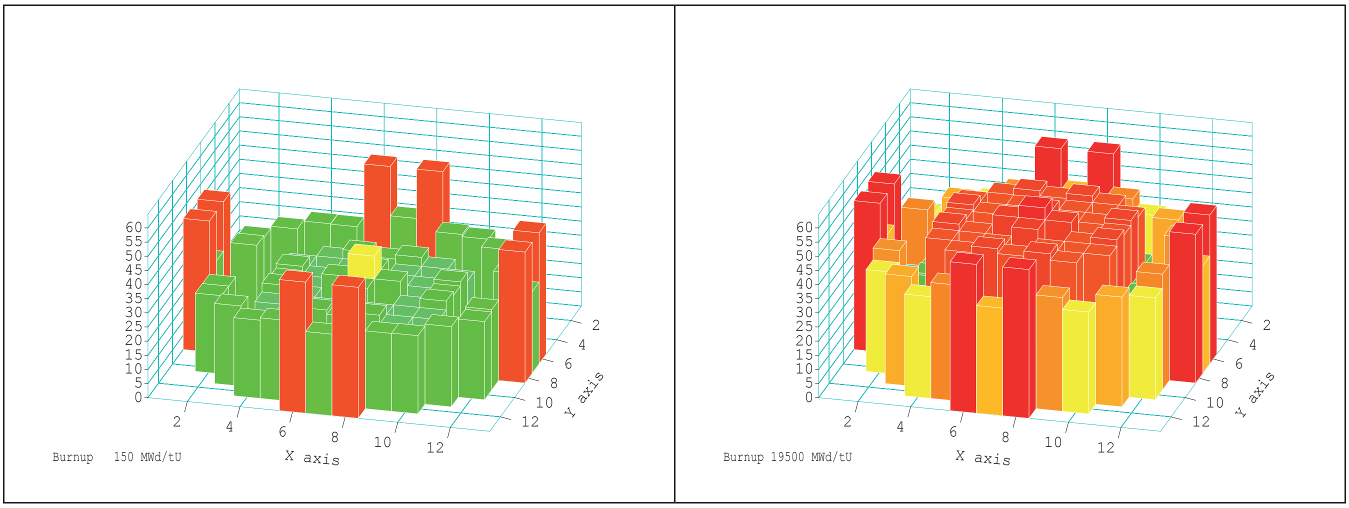

Figure 1. Cycle 26 distribution of FAs burnup, cycle burnup 150 MW/tU and 19500 MWd/tU

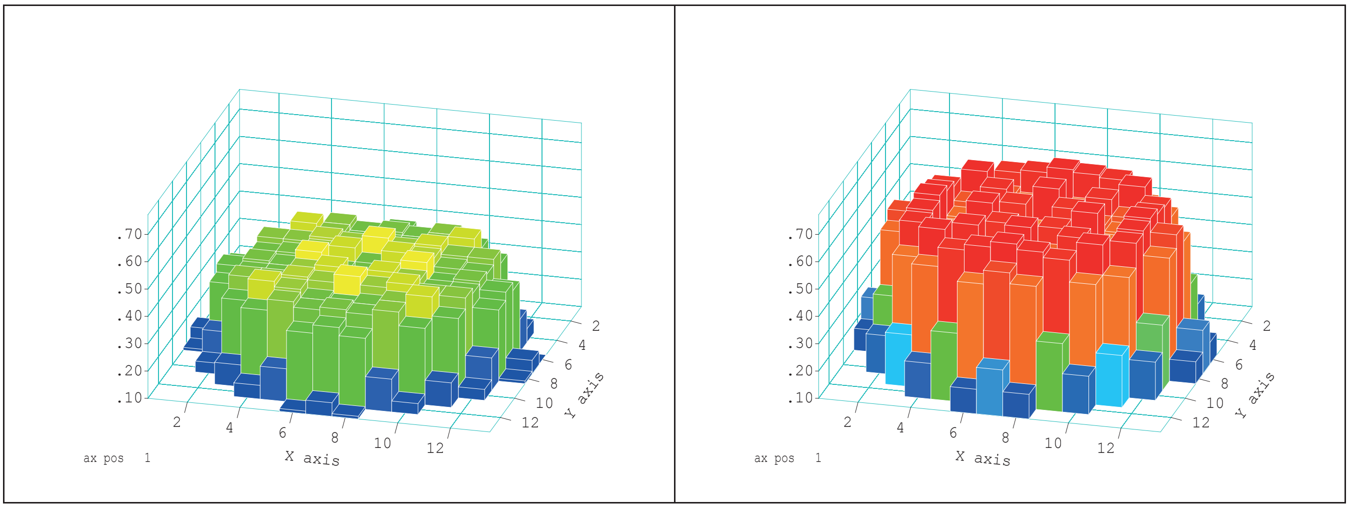

Figure 2. Increments in FAs burnup to get cycle burnup of 500 MW/tU and 20000 MWd/tU

ORIGEN simulation were performed for NEK Cycle 26, decay periods up to 3 hours, up to 100 hours, up to 30 days and up to 365 days. First time period is usual for core safety analyses, second is minimum cooling time before moving fuel from core to SFP, third is period usually analysed from RG 1.27 point of view (Ultimate Heat Sink (UHS) analysis), and forth is time scale important for long term calculation of fuel in SFP. The results for 3 hours, 100 hours, and 365 days are shown in Figure 3 to Figure 5. Decay heat due to fission product (FP), actinides (ACT), activation products (AP), and total decay heat power are given.

$$P_{sf,n} = \frac{\Delta burnup_{i,n}\left[\frac{MWd}{MTIHM}\right]\cdot m_{u,i}[MTIHM]}{t_n\left[d\right]} = \_\_\_\_\_\_\_[MW] \quad (1)$$

The plant specific calculation was performed for whole core inventory (121 FAs), on assembly by assembly basis. Approximate number of ORIGEN input lines is 10000 (that is why input preprocessor is necessary). The calculation can be performed for current cycle too (based on available PARCS results). It can be performed for current burnup (defined in preprocessor input), and can be used if unanticipated plant shutdown is experienced or if removal of the fuel to SFP is needed.

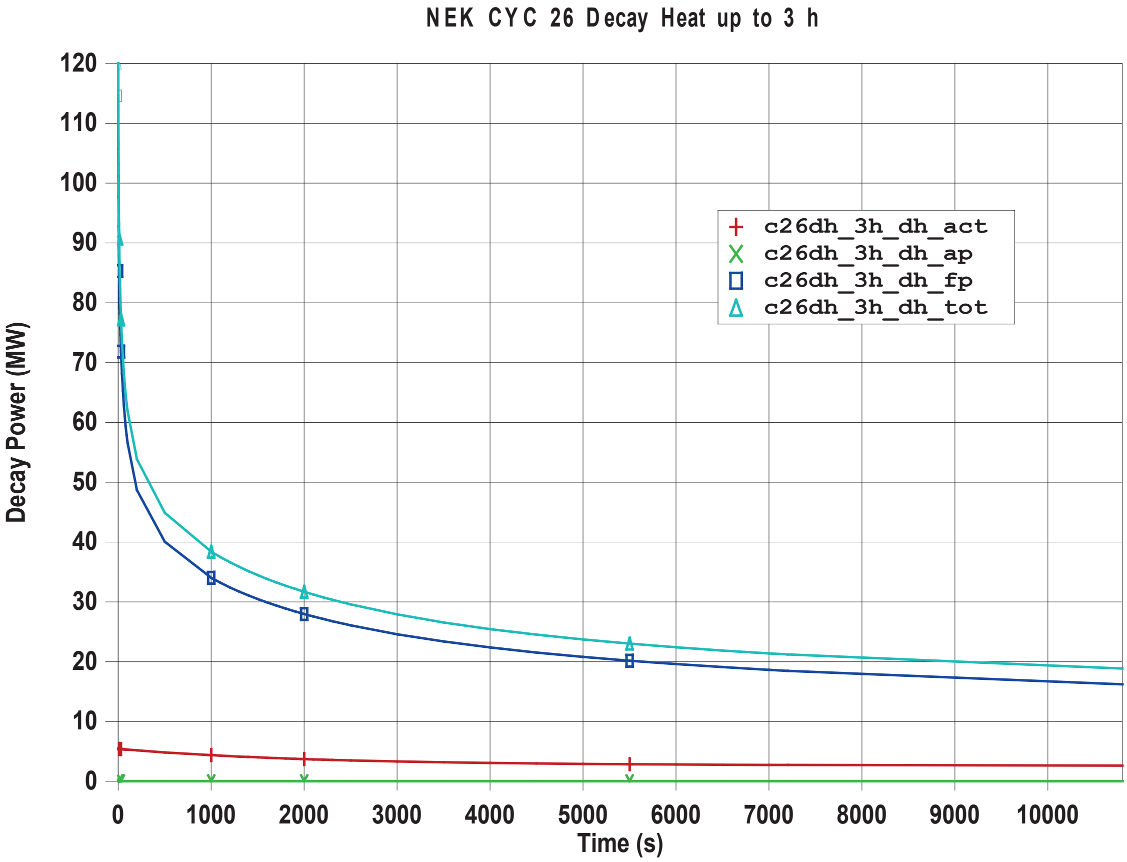

Figure 3. ORIGEN 2.1 calculated decay heat for cycle 26, up to 3h after shutdown

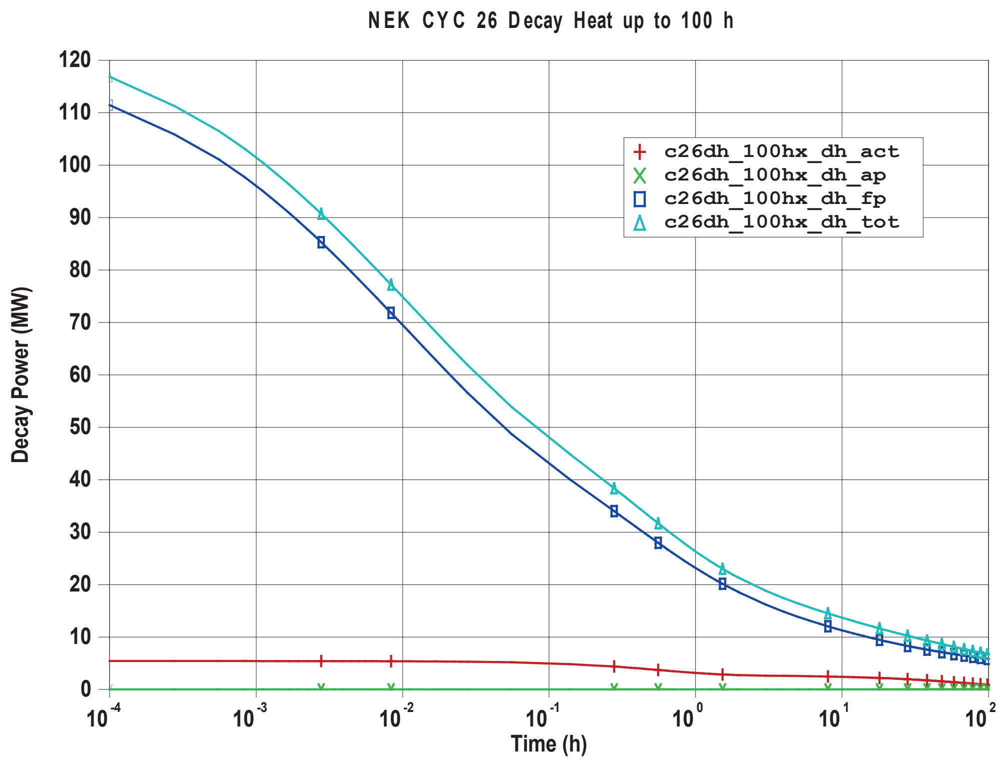

Figure 4. ORIGEN 2.1 calculated decay heat for cycle 26, up to 100h after shutdown

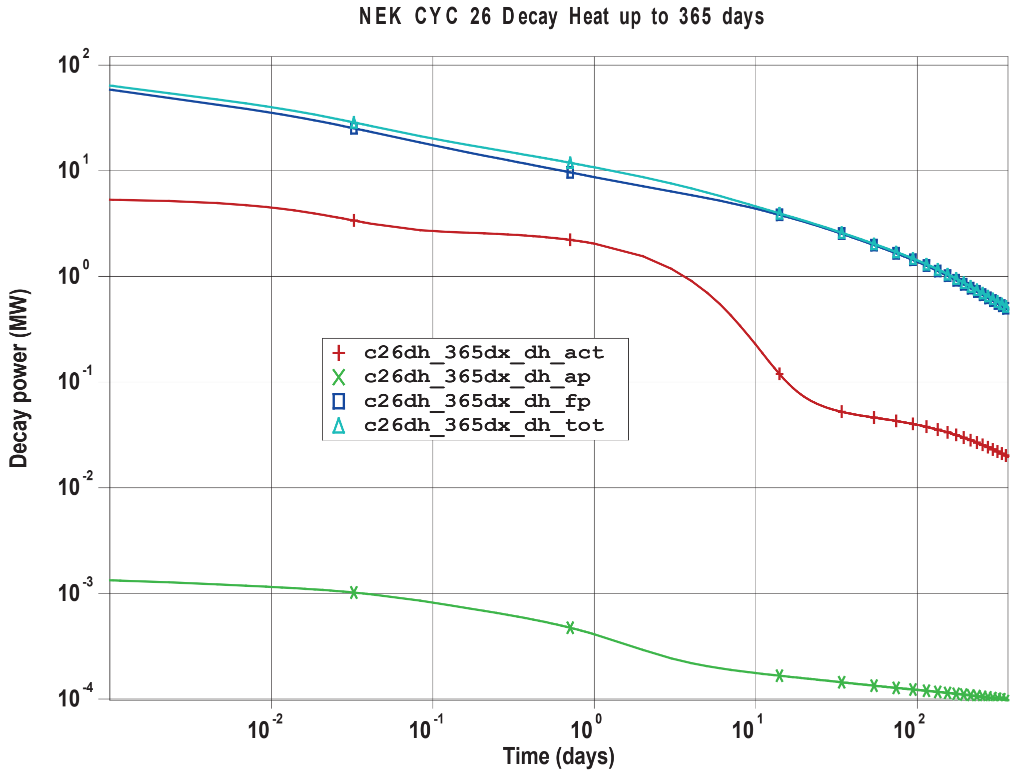

Figure 5. ORIGEN 2.1 calculated decay heat for cycle 26, up to 365 days after shutdown

3. SPENT FUEL POOL APPLICATION

Number of fuel assemblies in spent fuel pool is usually larger than current core loading and often approximate calculation is enough to check for time to boiling or time to fuel uncover or simple spent FAs statistics. Approximate number of spent FAs in NEK SFP is around 1200. In order to speed-up calculation process, detailed ORIGEN calculation can be replaced with fast decay heat calculation based on ANS Decay heat Standard. The decay heat calculation is part of graphical user application capable to provide simple FAs data base and manipulation (can be used during refueling). The same type of input data is used for both types of decay heat calculation.

3.1 ANS Standard Decay Heat Calculation

The reactor decay heat can be calculated using the ANSI/ANS-5.1-2005 standard [5], and small computer routine based on it. The calculation takes into account the time reactor core spent at power in operation before shutdown, and take into account 2σ uncertainties for decay heat power obtained after fission of 4 isotopes. For period of the interest for the calculation, conservative fixed uncertainty of 2% (one σ) was used. It is assumed that calorimetric uncertainty is 2% and that nominal power is 1994 MW (provided in input). Two uncertainties were combined as statistically independent to obtain overall uncertainty of 4,47%, used in the calculation.

The simple f90 modulef90 is used in the process of decay heat calculation. The code uses Tables 9 to 12 from the standard ANSI/ANS-5.1 in the calculation of decay heat after fission of following isotopes: U-235, Pu-239, U-238, Pu-241. αi and λi values from the tables as well as provided formulas (2) for calculation of energy release in MeV per fission were implemented in Fortran 90 programming language.

$$F(t,T)=\sum_{i=1}^{23}\frac{\alpha_i}{\lambda_i}\exp(-\lambda_i t)\left[1-\exp(-\lambda_i T)\right] \qquad \left(MeV\,/\,fission\right) \tag{2}$$

T is time spent at power, and t is time from initial fission till time when decay heat is needed. Both times are in seconds.

Practical implementation of above formula for decay heat power of isotope i at time t(s) after final shutdown, for operation lasting Tn seconds at power Pn (out of npow power intervals) is given in (3).

$$P_{di}^{'}(t,T_n)=\frac{P_{in}}{Q_i}\cdot\{\sum_{j=1}^{23}\frac{\alpha_{ji}}{\lambda_{ji}}\exp(-\lambda_{ji}(t+\sum_{n+1}^{npow}T_n))\left[1-\exp(-\lambda_{ji}T_n)\right]\} \tag{3}$$

Index i is used to label i-th isotope undergoing fission, n is for n-th power interval (counting from the interval when reactor was first at power), index j is used for internal summation of exponential terms for isotope i. Pin means power coming from isotope i in power interval n, and Qi means fission gain of isotope i.

The sample results for decay heat power (infinite operation time and plant specific operation time), for decay power and total released energy, are given in Figure 6 and Figure 7. The calculation was performed to provide required decay heat during verification of UHS capacity.

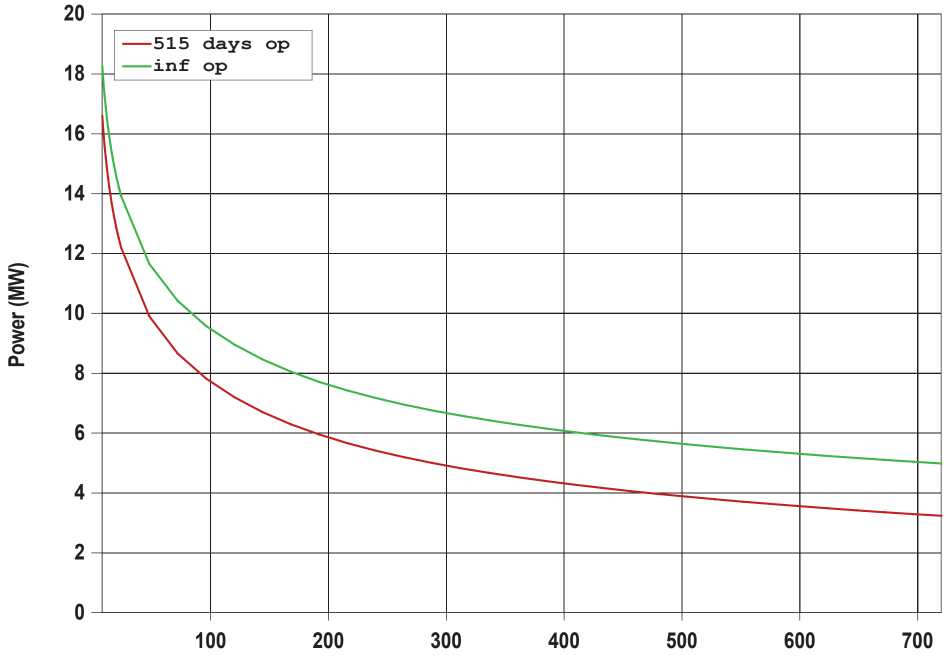

Figure 6. Power vs. time (h) for 30 days after shutdown calculated, ANS Std based routine

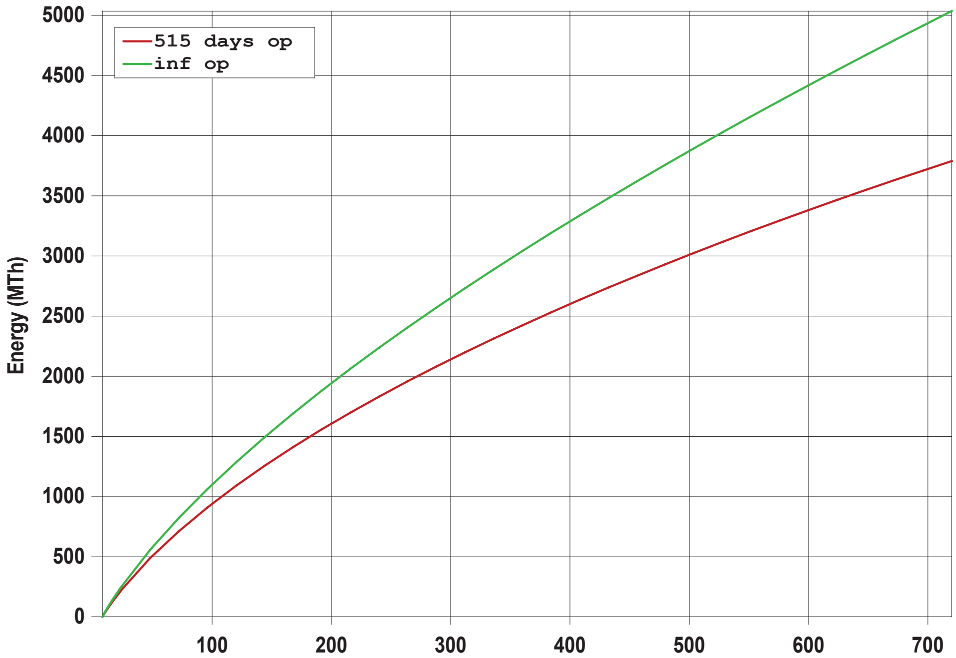

Figure 7. Energy vs. time (h) for 30 days after shutdown calculated, ANS Std based routine

3.2 SFP Graphical Interface

Decay heat power module is part of graphical application used to support different thermal hydraulics calculations of spent fuel pool. The application is able provide graphical representation of current position of spent FAs in SFP (Figure 8), based on USAr data [7], and associated data (time spent in pool for each FA (Figure 9), FA burnup (Figure 10), and FA decay heat power (Figure 11)), for any selected point in time. Decay heat can be obtained for any FA, any group of FA (e.g. rack), or whole pool. It is possible to provide time points and to get decay heat power versus time to be used in other codes or just to see time dependent decay heat in pool during depletion cycle (Figure 12) or during refueling.

The application has simple thermal hydraulic module capable to perform simple calculations of pool water heatup, time to boiling and time to fuel uncover for different initial scenarios (configuration of the pool, initial amount of water, presence of leakage and similar) [8]. Time to boiling dependence for different initial amounts of water and for increasing decay heat is shown in Figure 13. Calculated elevation of water in pool versus time for different scenarios is shown in Figure 14. It should be mentioned that used calculation is simple energy balance type of calculation and can be used as scoping calculation or as a preparation for more detailed calculations of the pool.

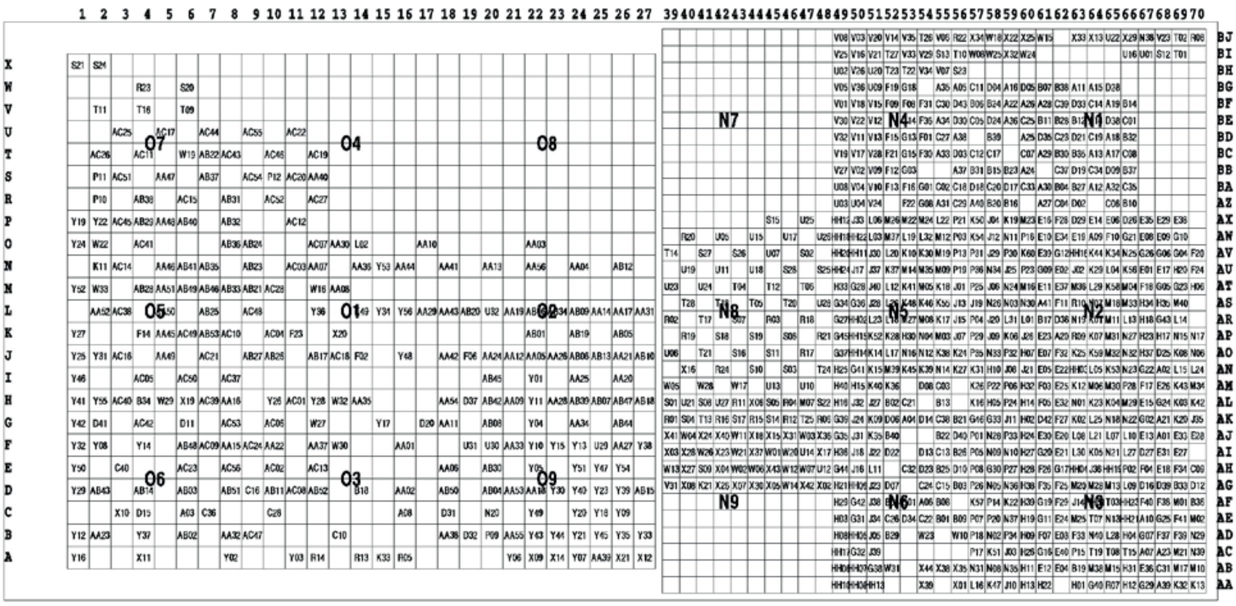

Figure 8. Layout of NEK SFP

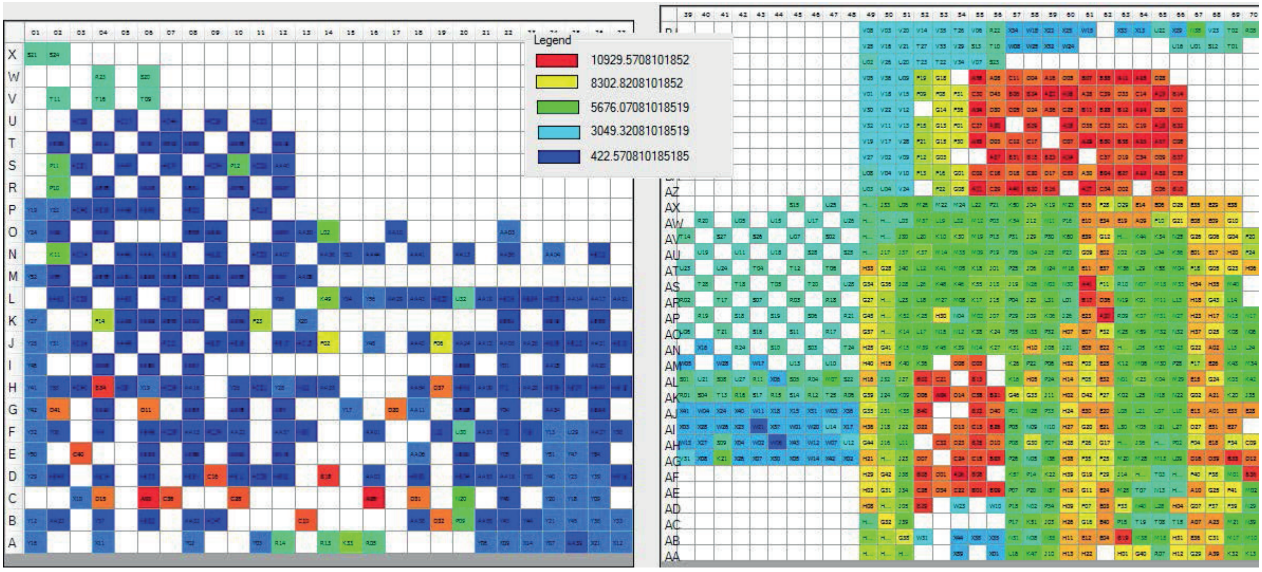

Figure 9. Time spent in pool (days) for different FAs (June 2013)

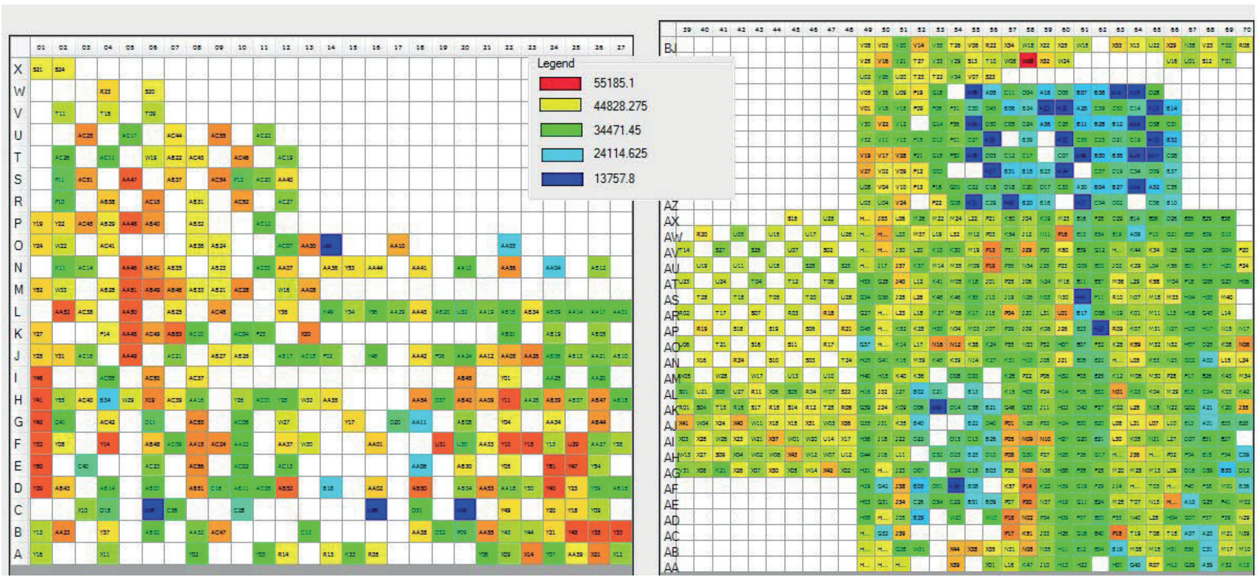

Figure 10. Burnup (MWd/tU) for FAs in SFP (June 2013)

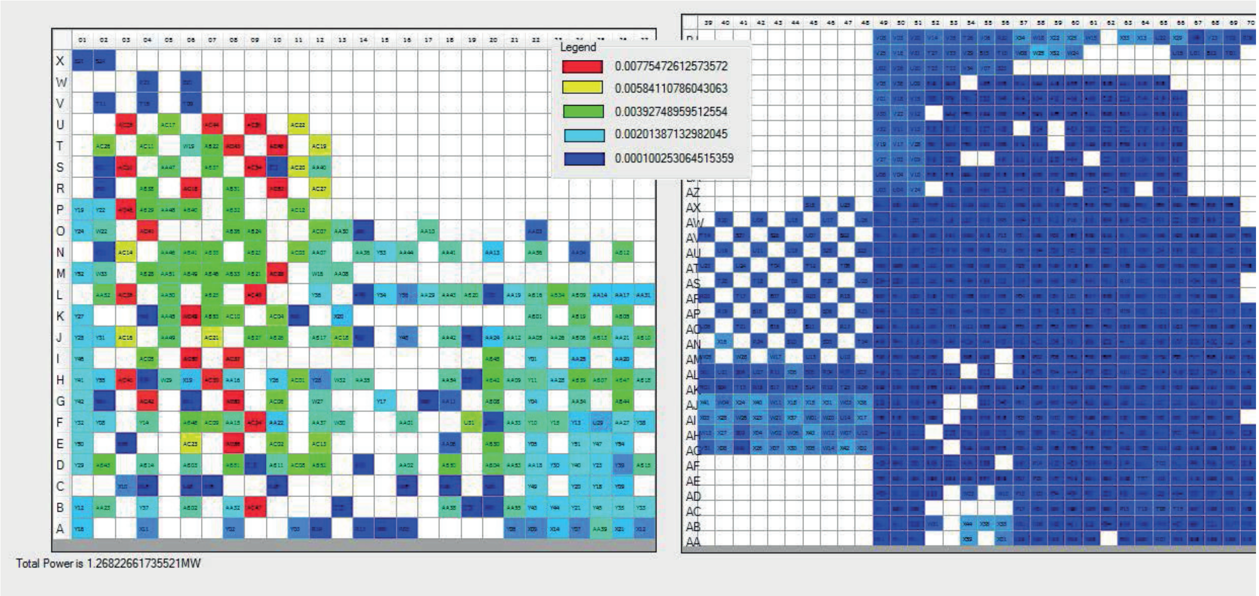

Figure 11. Decay heat (MW) for FAs in SFP (June 2013)

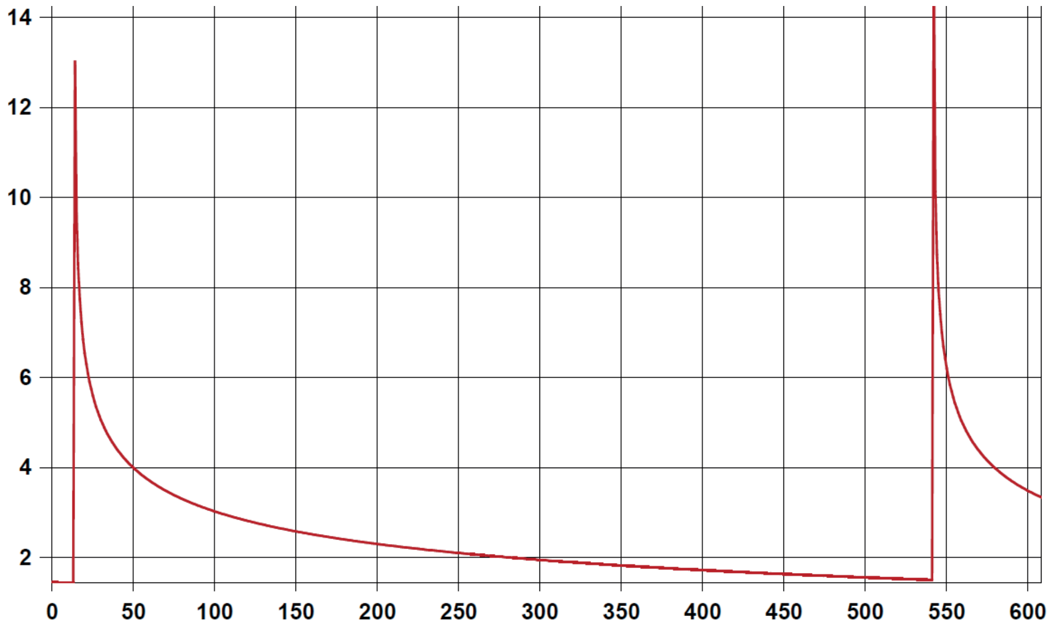

Figure 12. Total decay heat (MW) vs. Time (days) in SFP for two successive refuelings

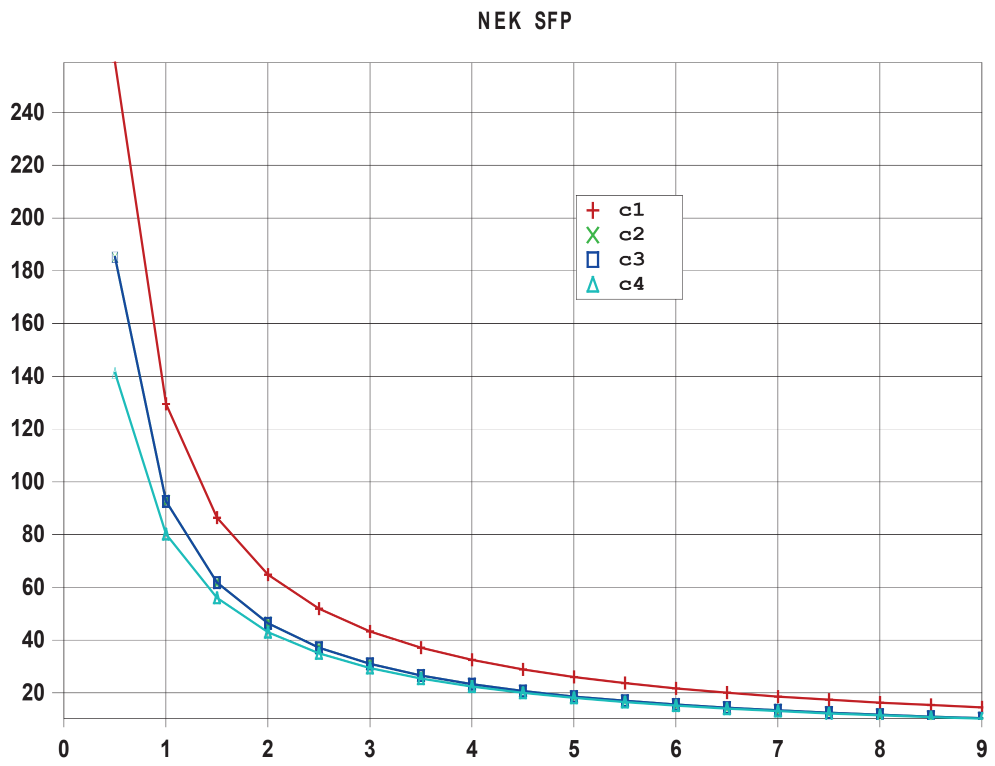

Figure 13. Time to boiling (h) vs. Decay heat (MW) for different scenarios

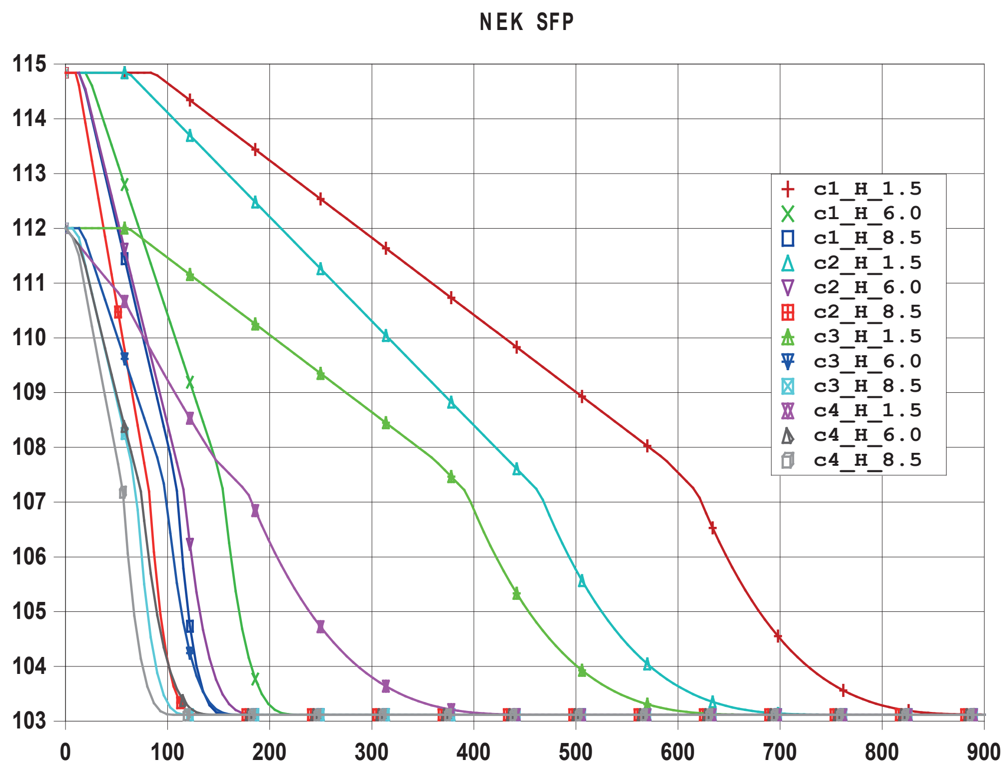

Figure 14. Elevation of water in pool (m) vs. time (h) for different scenarios and different level of decay heat (MW)

4. CONCLUSION

PARCS 3D burnup calculation can be used as effective means of providing power for ORIGEN depletion steps for plant specific decay heat calculation of fuel assembly basis. The developed procedure uses mix of well known codes and auxiliary routines to provide pre and post processing. FA burnups can be used to calculate plant specific decay heat for core or SFP. Due to amount of data needed for multi cycles calculation automatic pre-processor for ORIGEN input preparation (FA based depletion) is needed.

In addition to ORIGEN calculation fast module is available for both core and SFP decay heat calculation based on ANS standard decay heat calculation. In case of SFP it is part of graphical user application capable to trace position, time spent in pool, acquired burnup and current generated decay heat in each fuel assembly. The application is useful to predict total or per FA decay heat for other thermal hydraulics calculation in core or SFP. Simple calculation procedure is able to calculate water heatup for obtained time dependent decay heat or to calculate time to boiling and water level.

5. REFERENCES

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