Heat Deposition in Out-Core Devices of Research Reactors after Actuation of a Shutdown System Based on Reflector Tank Draining

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**Abstract**. Some high performance research reactor designs include a second shutdown system based on D2O reflector tank draining. Owing to the allocation inside the reflector tank of some irradiation devices, after the actuation of the second shutdown system these devices continue receiving nuclear heat deposition from the core with the drawback of being totally or partially uncovered. In uncovered devices, the D2O heat removal capacity is lost. In this situation, it is important to determine the time dependant evolution of the heat deposition and the resulting temperatures profiles in order to ensure the structural integrity of components. In the present work, some methodological alternatives are analyzed to determinate the heat deposition in the out-core devices after actuation of shutdown system based on reflector tank draining. For this study, neutron and photon transport calculations by Monte Carlo method using MCNP5-1.60 have been carried out, including the heat deposition contribution from prompt neutrons, delayed neutrons, prompt gammas, fission product decay photons and photons coming from structural materials reactions. Finally, it is proposed a calculation methodology that allows to estimate in a simply way the spatial and temporal behavior from each of the contributors. The results on Zircaloy-4 material from a generic D2O reflector tank research reactor are shown.

**1. Introduction**

Some high performance research reactor designs include a D2O reflector tank (i.e. OPAL, RMB and RA-10). The reflector tank main advantages are that as it is a good reflector, increases the system reactivity and also amplifies the available space with appropriate high neutron flux to accommodate more irradiation facilities.

Draining the D2O reflector tank introduce a large negative reactivity, enough to reach a safe subcritical configuration. Therefore, some designs include a Second Shutdown System based on D2O Reflector Tank Draining (SSS).

The actuation of the SSS uncovers totally or partially some of the irradiation facilities allocated inside the reflector tank, these uncovered facilities lose the D2O heat removal capacity.

A safe design needs to ensure a proper cooling of the reflector tank internals after the actuation of the SSS in order to preserve the structural integrity, avoiding potential deformations and damage. Consequently, an accurate methodology to estimate the time dependant heat deposition in reflector tank uncovered facilities is needed.

**2. Core and Reflector Tank Neutronic Model**

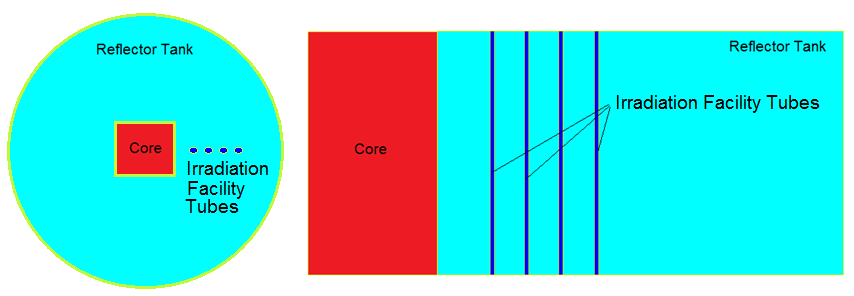
This study is carried on using a generic research reactor design. The model consists of a core surrounded by a reflector tank vessel.

The core consists of LEU MTR type fuels in a 5x5 array; the fuels is dispersed U3Si2 in Al matrix, and structural and cladding materials are Al 6061. The operational power is 30 MWth and an a generic equilibrium burn up distribution is used.

The reflector tank vessel is made of Zircaloy-4 and it is filled with D2O. Inside the reflector tank at different core distances, tubes of Zircaloy-4 filled with H2O simulate the irradiation facilities. Heat deposition in these tubes is studied.

Heat deposition in is calculated using MCNP5-1.60 . Modified cross section libraries which include fission product decay photon generation data are used.

A scheme of the generic research reactor design model can be seen in *FIG.1.*



*FIG. 1. Generic research reactor design model scheme.*

**3. Heat Deposition Calculation**

The heat deposited in each facility volume can be calculated integrating the equation:

[1]

Where:

1. : particle position vector, direction vector, energy and time
2. : angular flux
3. : microscopic total cross section
4. : energy release per collision

MNCP estimate the heat deposition contribution separately for neutrons and photons via track length estimation tallies in the volumes of interest. All the results are normalized by one fission neutron.

Photons can be classified as prompt or fission product decay photons, depending on their origin in the fission reaction or later fission product decays.

Heat deposition in reflector tank facilities are mostly produced by neutrons and photons from fission or fission product decay, but also, significant heat deposition is produced by photons and charged particles generated by capture reactions in structural materials, i.e. Aluminum from the fuel matrix and cladding.

The proposed approach is to obtain the contribution of each component separately in order to further evolve each contribution regarding its time dependence. Therefore, the overall heat deposition can be written as:

[2]

Where:

1. heat deposition due to neutrons
2. heat deposition due to prompt photons
3. heat deposition due to fission product decay photons
4. heat deposition due to photons, produced by neutronic activated aluminum decay, 27Al + n 🡪28Al 🡪28Si + β− + γ

In Al decay reaction, charged particles are going to be considered as local deposited; thus, only decay photon will contribute to heat Zircaloy-4 irradiation facilities.

Using different cross section libraries it is possible to differentiate the neutron, prompt photon, fission product decay photon and structural material decay photon contribution.

To obtain the total heat deposition is necessary to multiply the neutron and photon heat contribution per fission neutron by the total amount of fission neutrons. For a steady state situation the total amount of fission neutrons can be found using:

[3]

Where:

1. : thermal power output
2. : average neutron release per fission
3. fission energy release (~ 200 MeV)

Then the total heat deposition is:

**4. Time Dependant Consideration**

When the SSS actuates, two effects that modified the heat deposition in irradiation facilities appear:

1. A negative reactivity is introduced, that reduce the neutronic and photon population.
2. The loss of D2O in reflector tank diminishes the provided “shielding effect” for reflector vessel internals.

Both effects are strongly dependant of time. However, in this study only the first effect is going to be time dependant explicit modeled. The later, diminish of “shielding effect” due to the loss of D2O, will be considered but with the assumption of being instantaneous (no time dependant behavior)

**4.1 Time Dependant Model**

To model the time dependant behavior after actuation of SSS, the proposal is to multiply to each of steady state heat deposition contributor by an adequate time dependant function:

[4]

Where:

1. neutron time behavior
2. prompt photon time behavior
3. fission product decay photon time behavior
4. activated aluminum decay photon time behavior

**4.1.1 Neutron and Prompt Photon Time Dependant Function**

The neutron time population behavior can be accurately modeled using the well known point kinetic equations :

[5]

[6]

Where:

1. : neutron population
2. precursors population
3. time dependant reactivity insertion
4. group precursor decay factor
5. delayed neutron fraction
6. mean neutron lifetime

When considering prompt photons, them appear immediately after fission, thus its time dependant behavior depends on fission rate behavior with also follows neutron population time dependant behavior.

Consequently, time dependant heat deposition behavior from prompt neutron, delayed neutron and prompt photons can be approximately modeled by point kinetic neutron population function, thus heat deposition can be modeled as follows:

[7]

**4.1.2 Fission Product Decay Photon Time Dependant Function**

To model the time behavior of fission product decay photons it is proposed to use the nuclear decay heat curves from the American Nuclear Society :

[8]

[9]

Where:

1. : time after reactor shutdown
2. total operating period previous reactor shutdown
3. exponential fitting parameters

**4.1.3 Activated Aluminum Decay Photon Function**

To include the photons coming from the core due to Aluminum decay, the time behavior can be modeled using a simple exponential function:

[10]

Where:

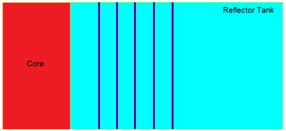
1. : 28Al decay factor

**4.2 D2O Draining "Shielding" Reduction Effect**

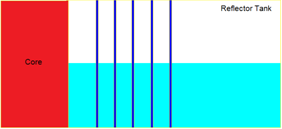
To take in account the effect of the D2O draining, steady state heat deposition at three different levels are calculated: 100%. 50% and 0%. *(see FIG.2.)*

It is important to remark that a steady state situation cannot be achieved with a drained reflector tank (subcritical configuration) but this calculation is necessary to find the reference initial heat deposition which then is going to be multiplied by the time dependant functions.

1. Tank filled at 100%



1. Tank filled at 50%



1. Tank filled at 0%



*FIG. 2. Reflector tank drained models.*

**5. Results**

**5.1 "Shielding Reduction" Effect due to D2O Draining**

TABLE I presents the change in heat deposition due to the reflector tank drain calculated in Zircaloy-4 tubes relative to the D2O full fill case.

It can be seen that, the greater the drained amount of D2O, the greater the heat deposition. It can also be noticed that this effect increases at further distances from the core.

When calculating heat deposition in Zircaloy-4 facilities after actuation of the SSS, the "shielding reduction” effect shall not be ignored.

TABLE I: Heat deposition increase respect to 0% drained reflector tank in Zircaloy-4 tubes. Statistical uncertainty is below 1.0 % at 1σ.

|  |  |  |
| --- | --- | --- |
| **Distance to the Core** | **50% Reflector Tank Drain** | **100% Reflector Tank Drain** |
| 30 | 5 % | 13% |
| 40 | 8% | 19% |
| 45 | 8% | 21% |
| 50 | 12% | 36% |
| 55 | 17% | 48% |

**5.2 Heat Deposition Contributors**

TABLE II, III and IV shows the percent heat deposition contributions for different reflector tank drain levels calculated in Zircaloy-4 tubes.

Due to the small absorption cross section of Zircalloy-4, neutron contribution is very small. Major contribution comes from prompt photons and in second place fission product decay photons.

It is important to notice that contributor’s percents do not change with the distances to the core or with the reflector tank drain percent. This independence allows for Zircaloy-4 tubes to use the same time dependant functions no matter the distance of the tube to the core or the tank drain level.

TABLE II: Heat deposition contributors for 0% reflector tank drain level in Zircaloy-4 tubes

Statistical uncertainty is below 1.0 % at 1σ.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Distance to the Core** | **0% Reflector Tank Drain** | | | |
| **Neutrons** | **Prompt Photons** | **Fission Product Decay Photons** | **Al Decay Photons** |
| 35 | 1% | 66% | 29% | 4% |
| 40 | 1% | 64% | 32% | 3% |
| 45 | 1% | 66% | 29% | 4% |
| 50 | 1% | 65% | 30% | 4% |
| 55 | 1% | 65% | 31% | 3% |

TABLE III: Heat deposition contributors for 50% reflector tank drain level in Zircaloy-4 tubes

Statistical uncertainty is below 1.0 % at 1σ.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Distance to the Core** | **50% Reflector Tank Drain** | | | |
| **Neutrons** | **Prompt Photons** | **Fission Product Decay Photons** | **Al Decay Photons** |
| 35 | 1% | 65% | 30% | 3% |
| 40 | 1% | 65% | 32% | 2% |
| 45 | 1% | 67% | 30% | 2% |
| 50 | 1% | 66% | 30% | 3% |
| 55 | 1% | 65% | 32% | 3% |

TABLE IV: Heat deposition contributors for 100% reflector tank drain level in Zircaloy-4 tubes

Statistical uncertainty is below 1.0 % at 1σ.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Distance to the Core** | **100% Reflector Tank Drain** | | | |
| **Neutrons** | **Prompt Photons** | **Fission Product Decay Photons** | **Al Decay Photons** |
| 35 | 1% | 64% | 32% | 2% |
| 40 | 1% | 65% | 32% | 2% |
| 45 | 1% | 67% | 30% | 2% |
| 50 | 1% | 67% | 30% | 3% |
| 55 | 1% | 65% | 32% | 2% |

**4.2 Time Dependant Heat Deposition**

Finally, *FIG.3* presents calculated results to the equation [7] (normalized to 1 MWth reactor power)in Zircaloy-4 irradiation facilities after actuation of SSS. Total and partial contribution it is also discriminated.

The time dependant negative insertion introduced by the actuation of the SSS to use in point kinetic calculation is shown in TABLE V.

TABLE V: Time dependant reactivity Insertion due to Reflector Tank Drain.

|  |  |  |
| --- | --- | --- |
| **Time (t)** | **Tank Drain (%)** | **Reactivity Insertion (pcm)** |
| 0 | 0 | 0 |
| 1.2 | 5 | 20 |
| 2.4 | 10 | 70 |
| 4.8 | 20 | 420 |
| 7.2 | 30 | 1200 |
| 9.6 | 40 | 2780 |
| 12 | 50 | 5600 |

It is necessary to remark that no consideration is made about the time dependant contribution of the "shielding reduction" effect.

It is seen that the first 10 seconds are dominated by the prompt photon contribution and further on time the dominant is the fission product decay photon contribution.

*FIG. 3. Time dependant heat deposition calculation in Zircaloy-4 irradiation facility after actuation of SSS.*

**5. Final Remarks - Conclusions**

This work studies the time dependant heat deposition in Zircaloy-4 irradiation facilities after SSS actuation.

A calculation methodology to get the heat deposition in these facilities using Monte Carlo method coupled with time dependant functions is presented.

Results obtained with this calculation methodology shows that D2O draining "shielding" reduction effect it is important and increase with the core distance.

It is found that largest contributors to heat deposition in Zircaloy-4 materials are prompt photons. Also, the contributors distribution do not change with core distance or reflector tank drain percent.

The analysis of the results of the time dependant heat deposition calculation shows that the first 10 seconds are dominated by the prompt photon contribution and further on time the dominant is the fission product delay photon contribution.

For further model improvement, it has to be studied and considered the time dependant draining "shielding reduction" effect contribution.

Complementary, time dependant behavior in materials with larger neutron contribution could be dealt in future works.

**6. References**

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2. GEORGE ROBERT KEEPIN, “Physics of Nuclear Kinetics”, Addison-Wesley Pub. Co., 1965.
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