Preliminary Review of SFUEL code for simulating the severe accident from the spent fuel pool under the complete drainage condition

13/05/2021

Jong-Hwa Park, Sang-Ho Kim, Jaehyun Ham, Rae-Joon Park

KAERI

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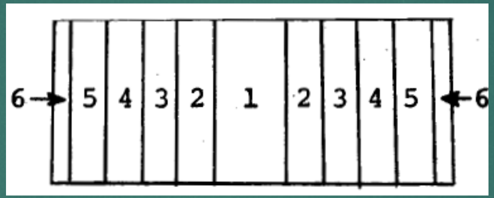
Background of review for the SFUEL code

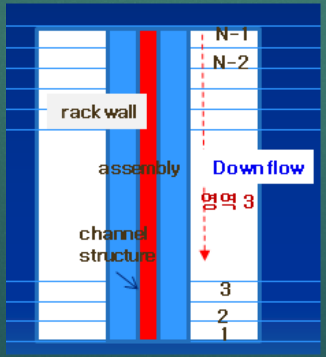
- The growing storage density requires more packed configuration of spent fuel arrangement within the spent fuel pool.
- It make the concerns on the safety for the spent fuel facility increase
- To evaluate the safety of such facility from severe accident, it needs to define the scope of postulated accident from the spent fuel pool
- The scope of accident was only limited to a complete drainage accident although the possibility of its occurrence may be extremely low (~1.0E-6/yr).
- It is because that its consequence are expected to be quite high.
- To facilitate the assessment of the safety and understand the conceptual design on the spent fuel pool against the severe accident under the complete drainage condition, it is recommended to develop a parametric tool.
- The purpose of this study is to get an insight to develop a parametric fast running tool for simulating a severe accident from spent fuel pool under the complete drainage condition.
- SUEL code, which was developed by SNL was selected as the reference code and The governing models such as the natural circulation of air in the channel and the oxidation of cladding by air were reviewed in this study.

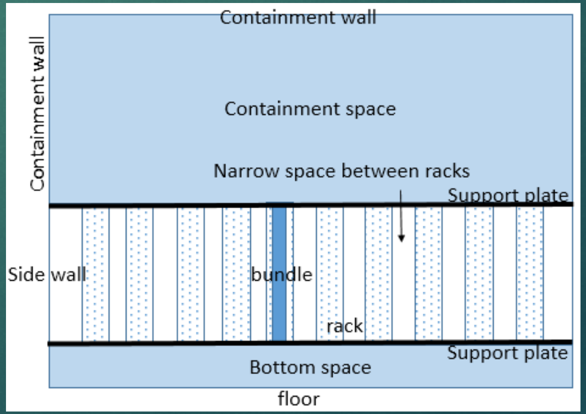
Nodalization of spent fuel pool

- The region where the fuel bundles are arranged were divided into several annular rings (6 rings). Each annular rings are characterized symmetrically by the different decay heat levels.



- The annular ring consist of fuel bundles, channel box, top and bottom support plate, rack , bottom floor and side walls.
- Open space above the pool was lumped together as a large containment region.





Governing equations for air flow

Air out flow mass = air inflow mass – oxygen consumption

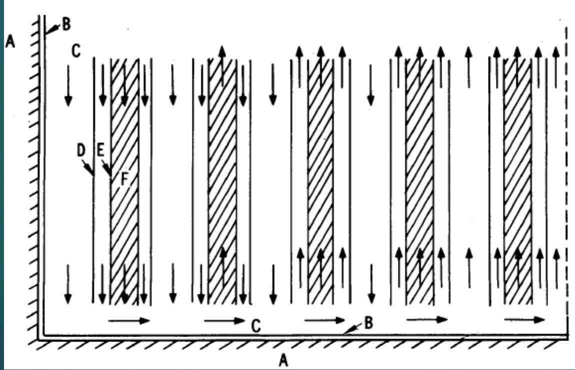
$$\sum_{bot}^{top\_end} \dot{m}_o = \sum_{bot}^{top\_end} \dot{m}_i - \int_0^L \dot{W}_{ox} P_w dx$$

Per rings

Pressure diffence = gravity head + friction head + friction through hole in plate

$$P_i - P_o = \int_0^L \rho g\, dx + \sum_0^L \frac{4}{D_H} \tau_w dx + \frac{(\dot{m})^2}{2\rho C_D^2} \frac{A_2^2 - A_1^2}{A_1^2 A_2^2}$$

Enthalpy change rate = (enthalpy_in) –(enthalpy_out)
- (enthalpy for the oxygen consumed in ox-reaction)
+ (convection heat from structures to air flows channels)

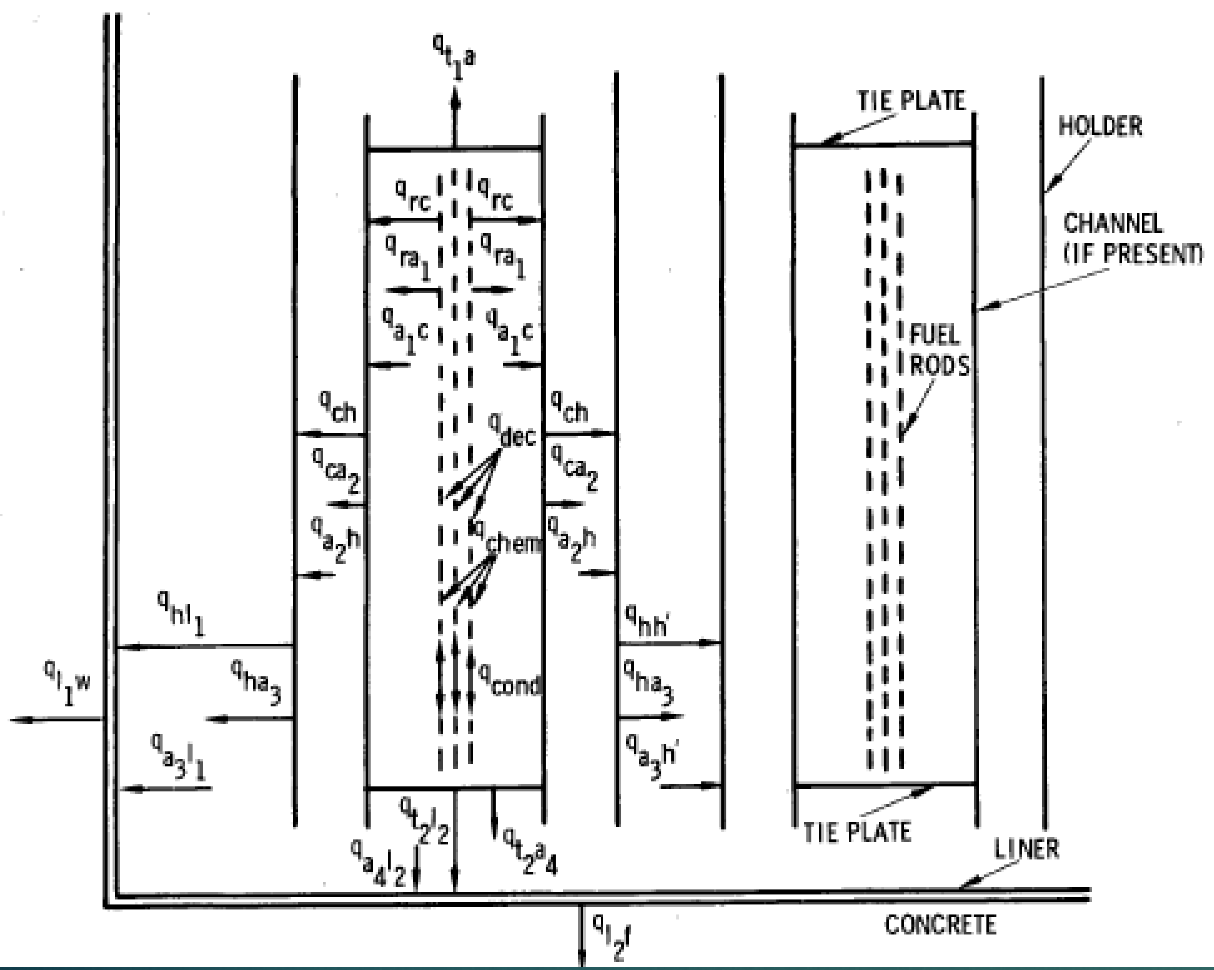


Prediction of air flow in the channels

- Inlet mass flow rates were assumed.
- Conservation equations are solved for each channel.
- Resulting exit pressuresobtained for upward directed vertical flows are compared with the pressure in the room above.
- Exit pressures obtained for downward directed vertical flows are compared with the calculated base floor pressure.
- Thereafter, the assumed inlet mass flow rates are adjusted in an iterative manner, using the ‘modified Newton-Raphson method’ until the pressure difference are become to negligibly small for each flow at exit.

$$(\dot{m})_{i+1} = (\dot{m})_i - \frac{f(\dot{m})_i}{\dfrac{f(\dot{m})_o}{d((\dot{m}))}}$$

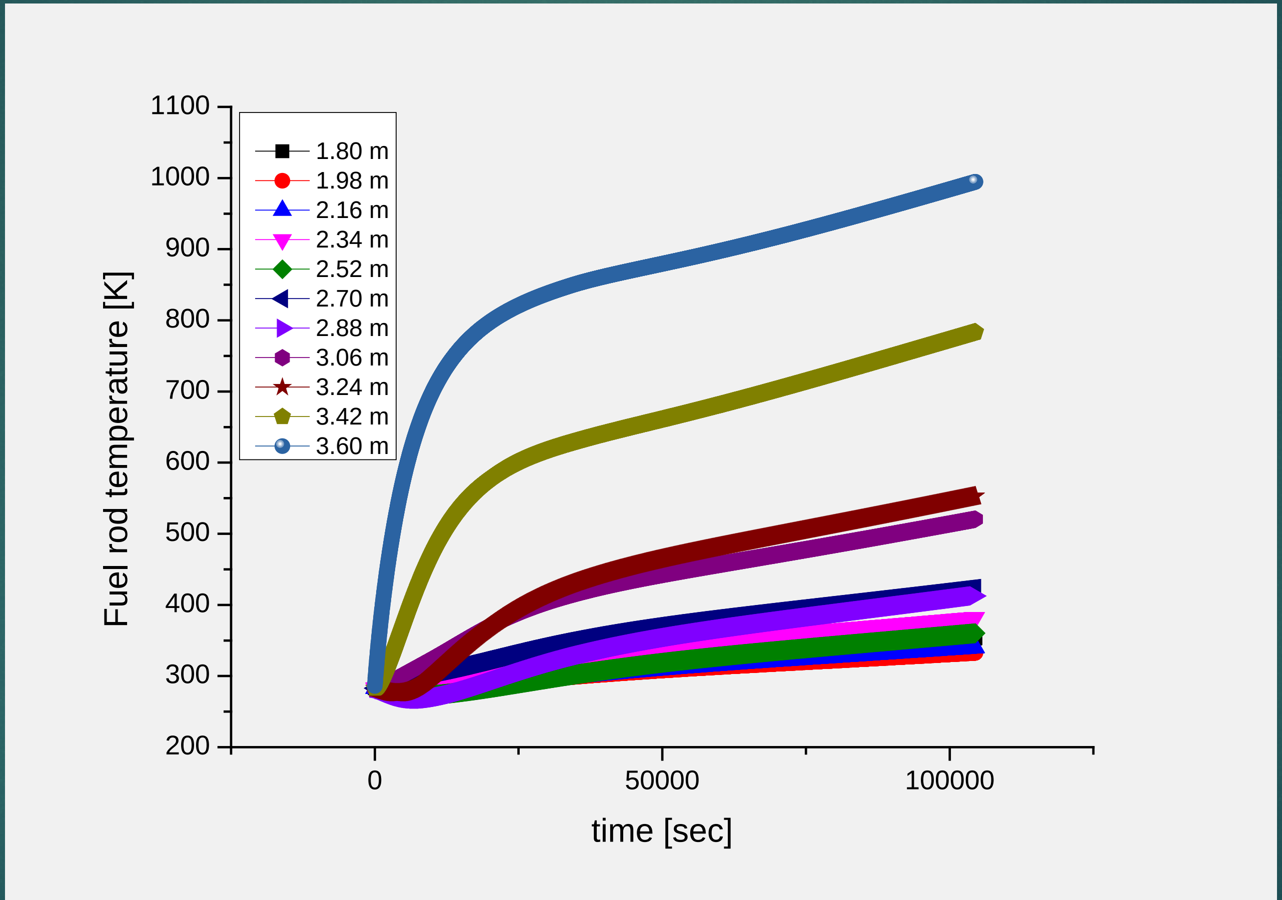
Overall Heat transfers



q_{dec}	q_{rc}	q_{t1a}	$q_{hh'}$	q_{ch}	q_{hl1}
q_{chem}	q_{ra1}	q_{t2l2}	q_{ha3}	q_{ca2}	q_{ha3}
q_{cond}	q_{a1c}	q_{t2a4}	$q_{a3h'}$	q_{a2h}	q_{a3l1}
		q_{a4l2}			q_{l1w}
		q_{l2f}			

t1= top plate
a= containment atmosphere
r= fuel rod
c= bundle channel box
a1= channel fluid
t2= bottom plate
l2= bottom floor liner
a4= fluid in between bottom plate and floor
f= bottom floor concrete
h= rack, h'= adjacent rack
a2= fluid between channel box and rack
l1= side wall liner
a3= fluid between outermost rack and side wall
w= side concrete wall
dec, chem, cond= decay, oxidation heat & axial conduct

Fuel rod temperatures in the center ring from SFUEL code



This calculation was terminated at 100,000 sec unfortunately. The air oxidation was not yet started.

Air oxidation equation in SFUEL code

(parabolic rate law: O_2 rich)

$$Zr + O_2 \rightarrow ZrO_2$$

$$2\, w \frac{dw}{dt}\bigg|_{parabolic} = K_o \exp(-E_a/RT)$$

w = weight gain (mg O_2 per cm^2)

t = time (seconds)

E_a = activation energy (cal)

R = gas constant = 1.987 cal/°K

T = temperature (°K)

$K_o = (mg\text{-}O_2/cm^2)^2\ S^{-1}$

1 Cal =4.1868 Joule

Based on mg-O_2/cm^2

$K_o = 1.15 \times 10^3$, $E_a = 27340$ ($T \leq 920°C$)
$K_o = 5.76 \times 10^7$, $E_a = 52990$ ($920°C < T \leq 1155°C$)
$K_o = 6.20 \times 10^4$, $E_a = 29077$ ($T > 1155°C$)

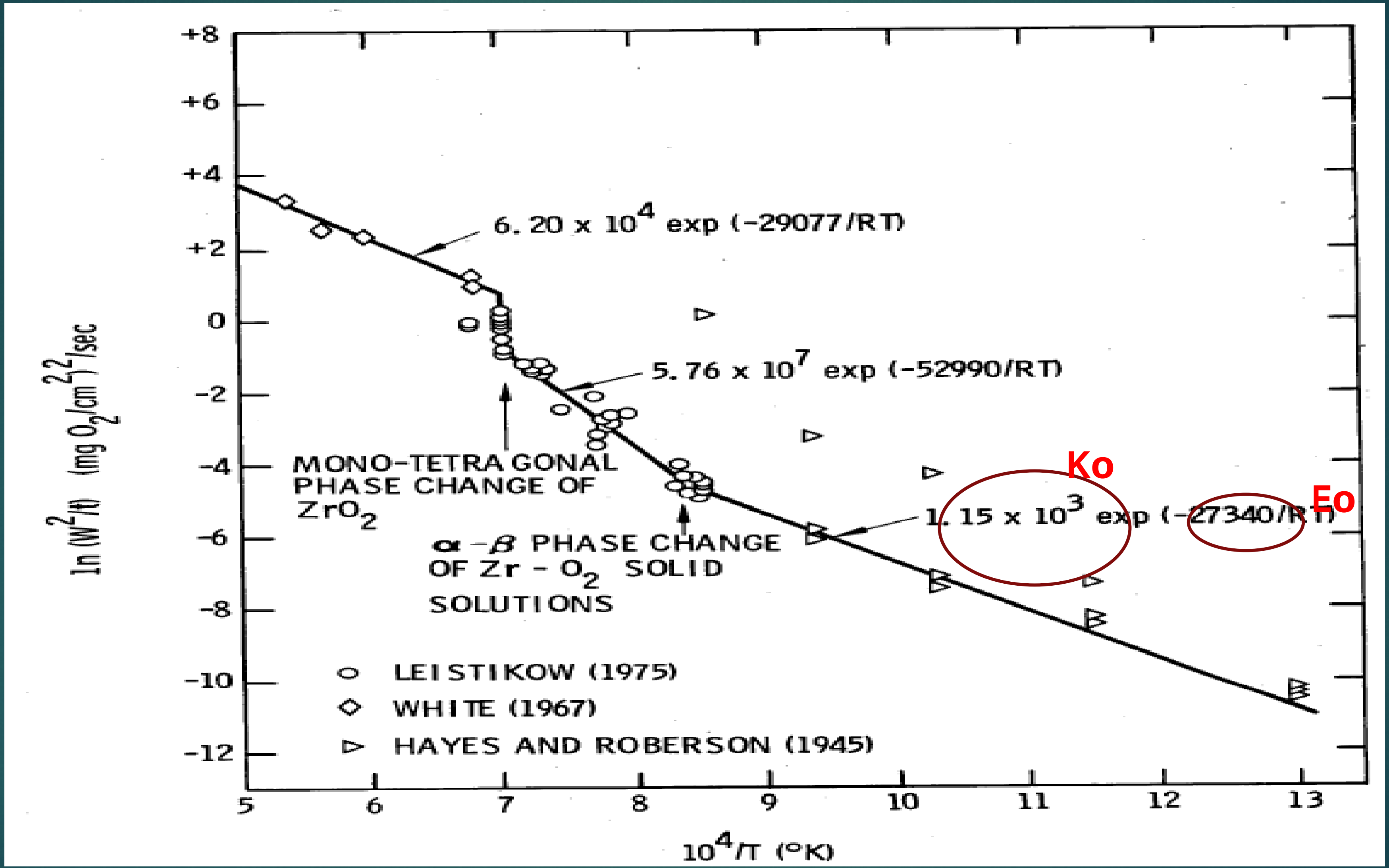
$$w^2 = w_o^2 + K_o e^{-E_a/RT} \Delta t$$

Based on **mg-O_2 consumed/cm^2**

$$w^2 = w_o^2 + C_1 e^{-C_2/T} \Delta t$$

Based on **mg-Zr consumed/cm^2**

Zircaloy Air Oxidation correlation vs T



Rate coef/eqt & convert to oxide thickness

Temperature range [K]	C_1 [(mg Zr/cm^2)^2*s^{-1}] [(mg O_2/cm^2)^2*s^{-1}]	C_2 (=E_a/R) [k] [cal/(1.987cal/k)]
T < 1193	9340 (**1150**)	13760
1193≤ T < 1429	4.68E+8 (**5.76E+7**)	26670
1429 ≤ T	5.04E+5 (**6.2E+4**)	14630

$$RATEK \equiv C_1 e^{-C_2/T}$$

Warning: **9340** = [(zr-mg/cm^2)^2 S^{-1}]
1150 = [(o_2-mg/cm^2)^2 S^{-1}]

$$w^2 = w_o^2 + C_1 e^{-C_2/T}\Delta t \Longrightarrow RCN^2 = RCT_o^2 + RATEK * \Delta t \quad \text{---- (1)}$$

RCT [mg-Zr/cm^2], Calcul 'RATEK' using above table values !!!

Divide both sides of eqt(1) by $(\rho_{zr})^2$

RCN= [mg-Zr/cm^2]

$$\frac{RCN^2}{\rho_{zr}^2} = \frac{RCT_o^2}{\rho_{zr}^2} + \frac{RATEK * \Delta t}{\rho_{zr}^2} \Rightarrow RCN^2 = RCT_o^2 + RATEK * \Delta t$$

RCN= [cm]

$$\frac{(RCN)^2}{\rho_{zr}^2} \Rightarrow RCN^2 = \left(\frac{mg-Zr}{cm^2}\right)^2 \times \frac{1}{\left(\frac{kg}{m^3}\right)^2}$$

$$= \frac{(mg-Zr)^2}{cm^4} \frac{10^{12}cm^6}{10^{12}(mg-Zr)^2} = cm^2$$

Rate of increase for the oxide thickness

$$\upsilon_{ox} = \frac{(RCN-RCT)}{\Delta t}$$

[cm/s]

Oxidation heat generation per mole of reacted Zr with oxygen

Use 262 Kcal/ mole Zr reacted

<- Melcor, RM COR-RM-80,
The same with ZrO_2/O_2 reaction heat
1.2065E+7 J/Kg-Zr

DELH [J/cm] = **Ox-heat generation by O_2/unit surf-area/unit radial ox-depth**

= [kcal/mol-Zr]*[J/kcal]/[g/mole-Zr]*[g/cm^3]*[unit surface area=1cm^2]

= 262*4186.8/(91.22)*{(6500)*10^{3}} /(10^6)*1

= 7.8164003E+4 [J/cm]

Oxidation Heat Generation Rate from clad per unit surf-area

Q_c= DELH*υ_{ox} [W]

Table of density for Zircaloy oxide

Temperature [k]	Density [kg/m3]
300	5800
1495	5640
1496	6040
3000	5710
3001	5992
3300	5992

Table of density for Zircaloy = *6500* kg/m^3

One mole of Zr = 91.22 g

One mole of O_2 = 32 g

Select mode of reaction rate

$$\left(\frac{dw}{dt}\right)_{parabolic} \geq \left(\frac{dw}{dt}\right)_{diffusion}$$

Select Parabolic eqt

$$\left(\frac{dw}{dt}\right)_{parabolic} < \left(\frac{dw}{dt}\right)_{diffusion}$$

Select Diffusion eqt

Results and summary

- The model to get the distribution of air flows in the channel can have a crucial effect on the overall thermal behaviors including the selection of heat transfer coefficients and the amount of air oxidation.
- In SFUEL code, “modified Newton-Raphson” method was applied to get the information on the air flows in the channel but it shows instability sometimes depending on the initial guessed mass flow rate for eacxh channel.
- It needs that more stable method to get the air flows in the channel to be developed for the fast running tool.