ABSTRACT

To support Nuclear Power Plant (NPP) Krško operation after the event in Fukushima Daiichi (2011) a need was expressed to develop the software that would be able to anticipate (via calculation) the thermo-hydraulic degradation of Spent Fuel Pool (SFP) in NPP Krško following loss of power to heat exchangers (loss of cooling capability) or rupture of the pool (loss of cooling inventory) in real time.

For that purpose a computer code called “Time to Boil”, that uses exact plant data, was developed in collaboration between NPP Krško and Institute Josef Stefan. It is iteration based calculation software that takes into account exact geometry and material information, decay heat of spent fuel assemblies, SFP water temperature and levels, the location and size of a potential SFP crack and calculates times needed for water to reach its boiling point and evaporate to a certain level.

The program is now used to predict the thermo-hydraulic phenomena in the NEK SFP in a case of a beyond design condition or how much time operators have to implement predetermined recovery actions.

The purpose of this paper is to explain the functional design, capability and limitations of the “Time to Boil” code and to demonstrate how it works in some specific cases.

1 INTRODUCTION

To support Nuclear Power Plant (NPP) Krško operation after the event in Fukushima Daiichi (2011) a need was expressed to develop the software that would be able to anticipate (via calculation) the thermo-hydraulic degradation of Spent Fuel Pool (SFP) in NPP Krško
following loss of power to heat exchangers (loss of cooling capability) or rupture of the pool (loss of cooling inventory) in real time.

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2 FUNCTIONAL DESIGN

The general idea behind the problem was to take vast amount of constructional and physical data along with given input parameters and scenarios, pack everything in a user friendly GUI and make it useful for NEK personnel.

Design of the so called SF System is the basis of the program. From the input point of view it holds all data regarding its structures and components whereas from the output point it represents the response to given events.

2.1 SF System Description

The SF System (Figure 1) is a compartmentalized structure which consists of a main pool (SFP) that holds Fuel Assemblies (FA), a Cask Loading Area (CLA) and a Transfer Chanel (TC) which are used for underwater fuel handling or transport. Last two are connected to the SFP with a passage that can be used to seal each compartment off. Note that SF System definition within this work is somewhat different that is originally used within NEK design documentation.

Figure 1: Virtual 3D model of the NPP Krško SF system with storage racks inside.
2.2 Input Data

Inputs for the program can be divided into two basic sections. The first one contains all design and physical parameters that are not foreseen to change much (Figure 2). They can be only changed by an administrator via a password input.

Figure 2: Inputs for design data and physical parameters.

The second one encompasses all the data that can be modified by a basic user to meet his required scenario (Figure 3). This includes parameters like:

- total water level and compartment configuration
- water temperature
- decay heat generated in FA's and their number
- system (liner) crack size and elevation, ...

Figure 3: User input page.
2.3 Calculation Methods

To cover all stages of heat up and evaporation an iteration based model of calculation was chosen. It enables the program to optionally modify time steps to keep changes of water level and/or temperature within acceptable range inside which changes of other parameters are negligible.

Calculations on their own are based on calorimetric equations and our assumption that all heat that is generated by FA’s is dissipated by water heat up or evaporation (no losses are included). One of the equations used in the program is shown below

\[
h_{n+1} = h_n - \frac{(h_n - h_{AFB})Pdt}{\rho A - \frac{h_n - h_{FB}}{h_n - h_B}} q_E
\]

where \( h_{AFB} \) represents the bottom of the FA active part, \( AFH \) the FA active height, \( h_{FB} \) the bottom of the FA, \( V_0 \) volume of all FA in the pool and \( V_1 \) volume of all racks in the pool, \( FH \) height of the FA and \( h_B \) the bottom of the pool.

2.4 Capabilities

Within predefined SF system configurations, that can be selected by the user, the program is capable of predicting the outcome of loss of power to pumps and heat exchangers with a simultaneous rupture of the SFP liner - leak off - as a worst case scenario. It plots the heat up curve/rate as well as level degradation curve/rate as a function of evaporation and/or leak off and from it evaluates times that are useful for the user.

As an addition a helper program (Figure 4) was built in that provides the user with information about FA’s on date residual heat based on pre-calculated cooling table that has to be updated each cycle or when a SFP inventory change occurs.

![Figure 4: Subprogram that returns information about FA’s residual heat.](image-url)
2.5 Limitations

Even though the program is able to anticipate evaporation of water below FA top (with a built in fact that a proportional part of FA is outside the water and that part of latent heat is transferred directly to air) it is not recommended to blindly rely on its results as physics of calorimetric transfer in that portion are somewhat unreliable. As water level decreases further down the FA the uncertainties grow. We predict that results are fairly reliable above half of the FA and degrade to much below this point.

In the current version of the program no alternative cooling capabilities are accounted for. In a case that ambient temperature is cooled or additional water is added via outside sources the total heat up time would only increase which is in accordance with a conservative approach.

The leak off part of the program is designed to take into account a circular break of a given cross-section and location (in reality probable cracks would be line kind). Due to this fact the program cannot be used to determine the size and location of a crack based on the measured level drop rate.

3 GRAPHIC USER INTERFACE AND RESULTS

To demonstrate how the program works a specific scenario was chosen that includes all programs capabilities at the same time. The simulation begins with a small crack (Figure 5). As water slowly leaks off, level decreases below the cooling system intake line which cuts off all cooling capabilities and water starts to heat up.

![Figure 5: Simulation starting point – leak off.](image)

After boiling is achieved, both leak off and evaporation contribute to level degradation down to the crack elevation (Figure 6). From that point on only evaporation degrades the level.
Figure 6: Evaporation is added to leak of level degradation.

The graphical interface helps the user to understand the flow of the scenario and prepares him for an anticipated event. Final results are presented in Figure 7.

Figure 7: Final results of the simulation.
4 CONCLUSIONS

The program is an essential and useful tool for NPP Krško personnel especially for Nuclear Fuel & Reactor Core engineering division. On its ground an online program for plants Process Information System (PIS) was developed, that evaluates the state of the SFP in real time.

Results of both programs are available for training of operational personnel.

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REFERENCES