A COMPLETE PASIVE SAFETY SYSTEM FOR CANDU 6- A NOT TOO FAR BRIDGE

UN SISTEM COMPLET PASIV DE SECURITATE PENTRU CANDU 6- UN POD NU PREA INDEPARTAT

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Abstract: In this paper we present the steps made in order to implement a passive safety system for a PHWR CANDU 6 power plant. After Fukushima accident, all nuclear plant owners had taken in consideration increasing safety of their nuclear power plants by increasing safety margins of plant in order to be able to withstand for a Station Black Out (SBO) accident. For Cernavoda CANDU 6 PHWR plant the owner increased electrical power supply by introducing new back-up safety diesel engines capable to be operated after a Design Based Earthquake (DBE). The proposed solution is based on Isolation Condenser (IC) system with natural circulation cooling. Supplementary the system is to be provided with non-condensable gases in order to self-regulate heat transfer inside IC heat exchangers. The solution is based on ANSALDO patent [8] designed to be implemented in LFR ALFRED demonstrator Reactor intended to be built at Mioveni Site

Keywords: passive safety system, CANDU 6, IC, SBO

Rezumat: In această lucrare prezentăm pașii parcursi pentru implementarea unui sistem pasiv de securitate pentru o centrală nucleară PHWR CANDU 6. După accidentul de la Fukushima, toți proprietarii de centrale nucleare au luat în considerare creșterea securității nucleare prin creșterea marginilor de securitate a centralei pentru a putea face față cu succes la un eveniment tip Station Black Out (SBO). Pentru centrala Cernavoda CANDU 6 PHWR operatorul a crescut alimentarea electrică prin introducerea de noi generatoare diesel de rezervă capabile să opereze dubă un cutremur baza de proiect (Design Based Earthquake (DBE)). Soluția propusă se bazează pe un sistem cu condensator izolat (IC), sistem bazat pe circulație naturală. Suplimentar sistemul este prevăzut cu gaze necondensabile cu scopul de se autoregla transferul de căldură în interiorul IC. Soluția are la bază un patent

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1. Introduction

In this paper we present step forward made in order to implement a passive safety level D system in CNE Cernavoda PHWR power plant. The starting point of the system is based on an ANSALDO patent [8] on an upgraded passive system provided with an IC system supplied with self-regulating non-condensable gases reservoirs. The IC system is isolated at normal operation and it is put in operation by opening of isolation valves. Opening of isolation valves is the only action of the operator of the plant permitted by passive safety level D classification of the plant. The system will be in operation only in SBO accident condition.

2. System Requirements

The system has a requirement to be able to act as reactor core heat sink in condition of SBO accident, using only passive components. The new designed system shall be able to transport decay heat from reactor core for at least 72 hours without almost any plant operator intervention. The only action allowed, as per Level D Passive system classification, is opening of the system isolation valves if a target pressure maximum value is reached. The system will have to be the first system to intervene in case of SBO accident. The IC system will have to retain all the secondary circuit cooling agent inventory, in order to preserve a natural circulation strong enough to cool down 2% of nominal heat flux of the reactor.

3. Engineering design

The system will be designed to be provided with one IC and one non-condensable tank for each steam generators of the plant. Each of the four IC will be on in an independent loop in order to have a redundancy of 3 of 4 IC. This means that in order to be successfully only 3 of 4 loops need to operational during SBO event. The main problem of a passive safety is that it cannot be regulate using actioned regulating valves. In order to control the IC
heat flux ANSALDO had patterned a self-regulating heat exchanger using pressurized non-condensable gases in order to reduce IC heat flux after the residual heat of reactor decrease with passing of time.

In order to design the system, the first step was to calculate total energy that is to be produced in reactor core after reactor trip during 72 hours. Calculation of energy of used fuel bundles from reactor core was made with computational code ORIGEN 2.2. The computation was made with hypotheses that the fuel burn degree is half of maximum for normal fuel burned in a life cycle. This hypothesis takes in consideration continuous fueling process specific for natural uranium CANDU reactor types. The result was the value of energy about $3.5 \cdot 10^5$ J (see Figure 3).

The decay heat power for PHWR CANDU 6 is presented graphical in figure 1 and figure 2 and numerical in Table 1.

Table 1 - Total Decay heat power for CANDU 6 NPP [1], [2]

| Time [seconds] | Time [hours] | Time [days] | Power percent [%] | Thermal Power [MW] | Duration [seconds] |
|---------------|-------------|-------------|-------------------|-------------------|-------------------|
| 0             | 0           | 0           | 100.000%          | 2180              | 0.1               |
| 0.1           | 0.00003     | 0.00000     | 6.530%            | 142.354           | 0.9               |
| 1             | 0.00028     | 0.00001     | 6.180%            | 134.724           | 1                 |
| 2             | 0.00056     | 0.00002     | 5.790%            | 126.222           | 3                 |
| 5             | 0.00139     | 0.00006     | 5.290%            | 115.322           | 5                 |
| 10            | 0.00278     | 0.00012     | 4.900%            | 106.82            | 10                |
| 20            | 0.006       | 0.000       | 4.450%            | 97.01             | 20                |
| 40            | 0.011       | 0.000       | 4.010%            | 87.418            | 40                |
| 80            | 0.022       | 0.001       | 3.560%            | 77.608            | 70                |
| 150           | 0.042       | 0.002       | 3.190%            | 69.542            | 150               |
| 300           | 0.083       | 0.003       | 2.810%            | 61.258            | 200               |
| 500           | 0.139       | 0.006       | 2.520%            | 54.936            | 250               |
| 750           | 0.208       | 0.009       | 2.300%            | 50.14             | 250               |
| 1000          | 0.278       | 0.012       | 2.140%            | 46.652            | 250               |
| 1250          | 0.347       | 0.014       | 2.010%            | 43.818            | 250               |
| 1500          | 0.417       | 0.017       | 1.900%            | 41.42             | 500               |
| Time [seconds] | Time [hours] | Time [days] | Power percent [%] | Thermal Power [MW] | Duration [seconds] |
|---------------|-------------|------------|-------------------|--------------------|-------------------|
| 2000          | 0.556       | 0.023      | 1.740%            | 37.932             | 3000              |
| 5000          | 1.389       | 0.058      | 1.320%            | 28.776             | 5000              |
| 10000         | 2.778       | 0.116      | 1.050%            | 22.89              | 5000              |
| 15000         | 4.167       | 0.174      | 0.948%            | 20.6664            | 5000              |
| 20000         | 5.556       | 0.231      | 0.882%            | 19.2276            | 10000             |
| 30000         | 8.333       | 0.347      | 0.790%            | 17.222             | 20000             |
| 50000         | 13.889      | 0.579      | 0.693%            | 15.1074            | 20000             |
| 70000         | 19.444      | 0.810      | 0.629%            | 13.7122            | 20000             |
| 90000         | 25.000      | 1.042      | 0.581%            | 12.6658            | 20000             |
| 110000        | 30.556      | 1.273      | 0.546%            | 11.9028            | 30000             |
| 140000        | 38.889      | 1.620      | 0.507%            | 11.0526            | 30000             |
| 170000        | 47.222      | 1.968      | 0.475%            | 10.355             | 30000             |
| 200000        | 55.556      | 2.315      | 0.448%            | 9.7664             | 59200             |
| 259200        | 72          | 3          | 0.381%            | 8.3058             | 259200            |

![CANDU 6 PHWR Reactor Decay power [%](image)](image)

Figure 1 – Decay heat power in percent from nominal power for CANDU 6 NPP [1], [2]
By considering that the active safety system is unavailable, this energy from the reactor core shall be removed only by the water from the DHR pool. There were available 2 solutions:

Solution 1: All energy shall be removed by heating pool water from 40°C to 100°C without evaporation. In this case the required water from pool
is about 15000 m³. The advantage of this solution is that -if in a limited volume- it could be placed inside containment. The main disadvantage of this solution is the very large volume of water to be placed inside containment, and for current configuration of CANDU 6 NPP there is not enough space to accommodate it inside.

**Solution 2:** All energy shall be removed by heating pool water from 40°C to 100°C with evaporation. In this case the required water from the pool scaled down to 1650 m³. The main advantage of this solution is that the volume is almost 10 times lower and can be accommodated inside containment. The main disadvantage of this solution is that it evaporates 1650 m³ of water in a contained space, the pressure inside containment shall increase over 100 bar (g) comparing with the maximum of 3.3 bar (g) allowed in the containment. In order to not dry-out the IC it has been decided to consider a 2000 m³ pool; in this way all four ICs remain under water for 3 days.

Taking into consideration the 2 available solutions, it has been concluded that the pool cannot be accommodated inside containment and have to be installed outside the containment.

In the DHR system design the natural circulation of fluids has been considered as consequence of SBO design condition. This requirement leads to pool positioning as close as possible to the containment.
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- one from reactor core to steam generation;
- the second one, from steam generation dome to DHR pool.

Figures 4 and 5 show the general arrangement of the pool inside Cernavoda Unit 2 N.P.P.

Figure 5 - General arrangement - lateral view of the DHR system

In case of natural circulation, the thermal-hydraulic analyses show that the cold source have to be at about 10 m above the hot source. The elevation of steam generator dome is about 30 m above the ground [3] [4]. In conclusion, the pool has to be at least at 40 m above the ground. In order to accommodate this high elevation of the pool, one should consider the construction of a water tower near the containment. A section through the tower is shown in Figure 6. The final elevation of the tower will be assessed based the on RELAP5 thermal hydraulic analyses.
In order to size the IC heat exchangers, it has been considered an availability of 3/4 heat exchangers, a total heat flux of 2% of the nominal thermal power of the reactor, corresponding to 20 minutes delay after the SBO is initiated. This led to a heat exchange surface required of about 130 m² for each IC; this surface was considered as corresponding to 220 tubes with a diameter of 38.1 mm. The conceptual design of the heat exchanger can be seen in Figure 7.

The system has a 3/4 redundancy, only 3 ICs are required to start in order to remove all the energy generated in the reactor core. Supplementary, the headers of ICs were not taken into consideration in the heat exchange calculation; this leads to an additional conservative calculation margin.

Each IC will be connected to a non-condensable gases' recipient of about 10m³. Most probable the non-condensable tank will be located below the ICS. The gas inside will be nitrogen and the initial pressure and volume of the recipient will be determined/confirmed by RELAP5 calculations.
The process diagram, without maintenance subsystems (filling, draining, heat trace cables), is presented in Figure 8.
The thermal-hydraulic simulations using RELAP5/MOD3.2 imply the modelling of the significant systems of the CANDU 6 NPP. The systems considered in the simulation (Figure 9) are: Heat Transport System (HTS), Pressure and Inventory Control System (PICS). Also, there is a RELAP5/MOD3.2 model for Emergency Core Cooling System (ECCS).

In Figure 9 are shown the active zone modelled with 2 loops in "figure of eight" which have 2 equivalent passes (Zone 1, ..., 4), the reactor inlet header (RIH 102, 104, 106 and 108) and outlet header (ROH 103, 101,105 and 107), as well as the steam Generator 301, 302, 303, 304.

The components included in thermal-hydraulic model of the active zone of CANDU 6 NPP are specific RELAP5/MOD3.2 components, i.e. branch, pipe, snglvol, tmdpvol component (interconnected with simple junction), and pump, valve, separator component.

![Figure 9 - Main scheme of CANDU 6 NPP used in RELAP5/MOD3.2 computer code [5]](attachment:figure9.png)

For the feedwater that supplies the steam generators and removes the heat from the primary coolant and which has a separate circuit (see Figure 10),
an input model has been also created using RELAP5/MOD3.2 code and has been included in the final input model of CANDU 6 active zone.

Figure 10 - The scheme adopted in the modelling of the secondary side of the steam generator

Figure 11 - The scheme adopted in modelling the isolation condenser coupled to Steam Generator 1 and 2

The model of plant was made in order to simulate SBO accident for 12000 seconds. In Figure 12 it is presented pressure in steam generator and
in IC during 12000 from initialization of event. The model will be upgraded, now is in testing and validation period in order to simulate complete natural circulation in PHTS, secondary circuit and IC System.

![Graph of pressure evolution](image.png)

**Figure 12 - Evolution of pressure in the steam generators and in the passive isolation condense during SBO event**

### 5. Conclusions

The current situation as per [6] and [7] concluded that Cernavoda CANDU 6 has 23 hours of time in order for operation in complete passive safety condition (SBO accident) in order to preserve integrity of combustible bundle.

In this paper we presented steps forward in order to implement a complete new passive safety system for CANDU 6 NPP, a system derived from ALFRED LFR demonstrator reactor project, a system capable to increase window time opportunity for main operator in order to find a proper heat sink from existing 23 hours to at least 72 hours-time. The work is very complex and it needed a interaction between engineering design from CITON and modelling in RELAP5 from ICN of the system. The modelling of the system is required in order to validate elevation of IC pool and diameters of
connection pipes in order to have enough natural circulation in secondary circuit. Moreover, RELAP5 model is compulsory to verify IC heat exchanger heat flux with non-condensable gases and feasibility of synchronously of two natural circulations in PHTS and in secondary circuit.

RELAP5 modelling of system is to be integrated with engineering design, because the system was design from scratch, CANDU hadn't yet provided a system capable to operate in passive safety conditions for more than 24 hours.

RELAP5 modelling of heat transfer with non-condensable gases and natural circulation of water/gases combination is to be validated with experimental data in PIACE Project at ENEA Laboratory.

We are confident that in very short time the system will have a complete technical specification with isometric drawings, layout plan, date sheet, PID, ATH with RELAP5 model and a very good integration in existing safety principle and proceedings of the CANDU 6 Cernavoda NPP.

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