Development of educational and training simulator PCTRAN for SMART

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1. Introduction

SMART is a 330 MWth pressurized water reactor with integral steam generators and advanced safety features. The unit was designed by Korea Atomic Energy Research Institute (KAERI) for electricity generation as well as thermal applications such as seawater desalination. SMART has its unique in-vessel pressurizer, helical coil once-through-steam generators, and canned circulation pumps. It is equipped with both active and passive heat removal systems. In the event of a severe accident resulting hydrogen in the containment, there are passive auto-catalytic re-combiners (PAR) to reduce its concentration. They are all closely simulated in the PC-based simulator PCTRAN/SMART for training and education.

2. Methods and Results

SMART can use all its steam for electricity generation for a total of 110 MWe, or extract the steam at its low-pressure turbine to a multiple effect distillation (MED) with thermal vapor compressor (TVC) for desalination. The electricity output will be reduced to 90 MWe with 40,000 tons of fresh water production per day. MED-TVC has a gain output ratio (GOR) about 13 for the distilled water to the motive reactor steam. Some normal and accidental cases have been conducted. They include normal startup, power escalation, shutdown and cool-down using normal helical coil once-through steam generator (HCSG) and shutdown cooling system, loss of coolant accidents and station blackout (SBO) Fukushima type accident. Despite core damage and hydrogen generation is virtually impossible to occur, the simulator is capable to perform an intentional loss of passive residual heat removal (RHR) cooling event with hydrogen in the containment. Then start of the PAR suppresses the hydrogen to non-combustible level.

Shown below in PCTRAN/SMART graphic user interface (Fig. 1), the center reactor vessel contains the pressurizer at the top. Eight HCSGs are lumped into two and four canned motor pumps are modeled inside the vessel. In the upper left chemical and volume control system (CVCS) panel, the charging pump and letdown valve control the pressurizer level and coolant chemistry. Boron concentration can be raised or lowered simply by clicking on the + or – buttons respectively. The level, pressure, their respective set points and safety relief valve flow rate are displayed near the pressurizer. Below CVCS is the shutdown cooling (SDC), safety injection (SI) and containment spray (CS) control panels. In the upper right corner there is turbine/generator control panel. Turbine power can be varied by setting the demand and change rate. The reactor and entire plant control will follow as designed. Right underneath is the steam generator control of its header pressure. Feedwater flow is adjusted to match the desired SG level. Further down is the reactor protection system (RPS) with the reactor scram and, trip and AC power buttons. The actuated trips are indicated in red. The engineered safety feature actuation system (ESFAS) that start the SI and CS trips are also indicated by red flags. Middle lower right is the reactor core control. Rod assemblies in their total withdrawn percentage can be changed to adjust the core power. In this mode the turbine follows the reactor. The neutron flux, reactivity, core fuel temperature and void fraction are displayed. To its left is the containment panel to show its thermal-hydraulic conditions. The in-containment refueling water storage tank (IRWST) provides water for SI and CS pumps. It also collect water spill from a loss of coolant accident. There is mechanism to shift water into the reactor cavity in the event of core-melt to cool the vessel bottom. SMART has both passive and active heat removal systems and severe accident mitigation hydrogen re-combiners. They are all closely simulated in normal and accident conditions.

In addition to turbine-generator for electrical production, low pressure steam can be extracted for desalination to generate about 40,000 tons of fresh water per day by a MED-TVC device. The electricity production would be reduced from 110 MW to 90 MW. In PCTRAN MED-TVC modeling, we assumed 25% of total turbine steam is extracted as the motive steam at 0.3 MPa. Going through 4 modules of 14 effects each with top brine temperature at 70°C, a total of 40,000 tons of distillate per day is produced at a gain ratio (GOR) about 13. The electricity, fresh water and process heat can supply a city of 100,000 populations.

For a Fukushima type total loss of offsite and onsite power event, there is no heat sink via the steam dump and SDC systems. The passive RHR (PRHR) system is automatically turned on by opening the drain valve downstream in the steam line submerged in the Emergency Cooling Tank (ECT) of the PRHR system. It is located 10 meters above the SGs outside the containment. Natural circulation prevails to condense the steam from the HCSGs and returns into the SG feedwater lines. In this run about 500 seconds after reactor shutdown, PRHR is turned on. In the following mimic the steam line valves to the PRHR and the drain line valve are opened in red. All normal AC-powered pumps and valves are disabled. Transient plots for the first couple hours after shutdown using PRHR cooling are shown in Fig. 2. Water in the tank is heated up to boiling in about 4 hours. The reactor remains in high pressure but under control. Amount or water in the ECT can maintain the reactor core cooled to 200℃ in 36 hours.

In order to simulate small break loss of coolant accident, the break area of 5 cm2 is entered for a feedwater line break. The reactor is quickly shutdown upon the low coolant pressure signal. Turbine trip follows and then AC offsite power is assumed lost. The PRHR is automatically started and the emergency diesel is powered to start the SI system pumps. In the following transient figures as shown in Fig. 3, the SI flow exceeds the coolant loss within 100 seconds. The pressurizer empties and a void develop in the reactor vessel. However the bubble never drops below the top of the fuel, so the reactor is never in danger as the PRHR is removing the decay heat to the ECT.

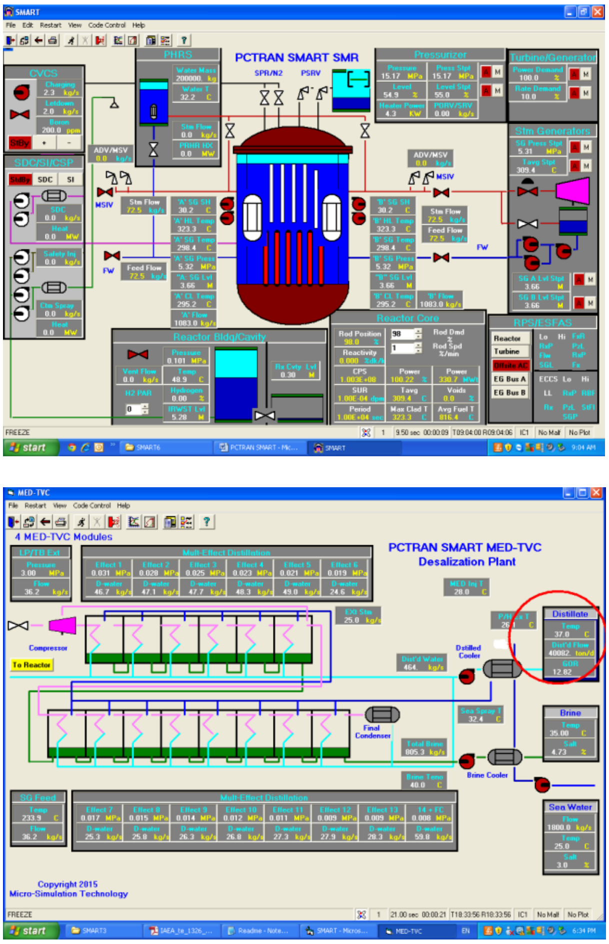

Fig. 1. PCTRAN SMART Small Modular Reactor Simulator with MED-TVC

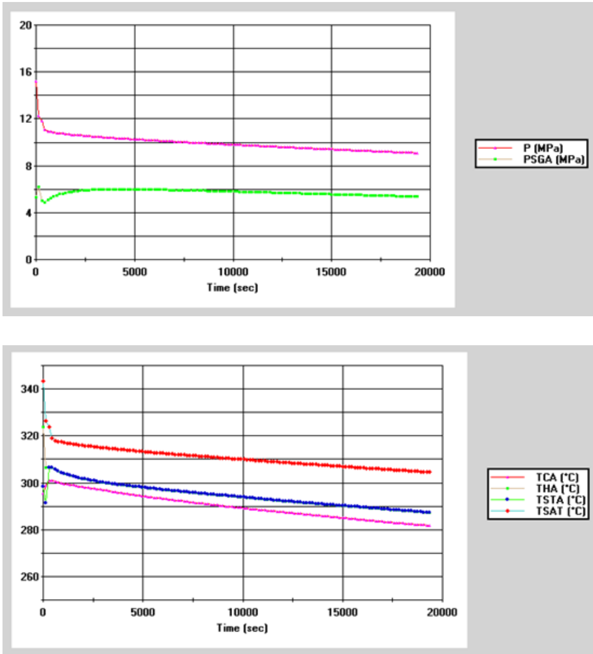

Fig. 2. Passive RHR Cooling Simulation in Station Blackout

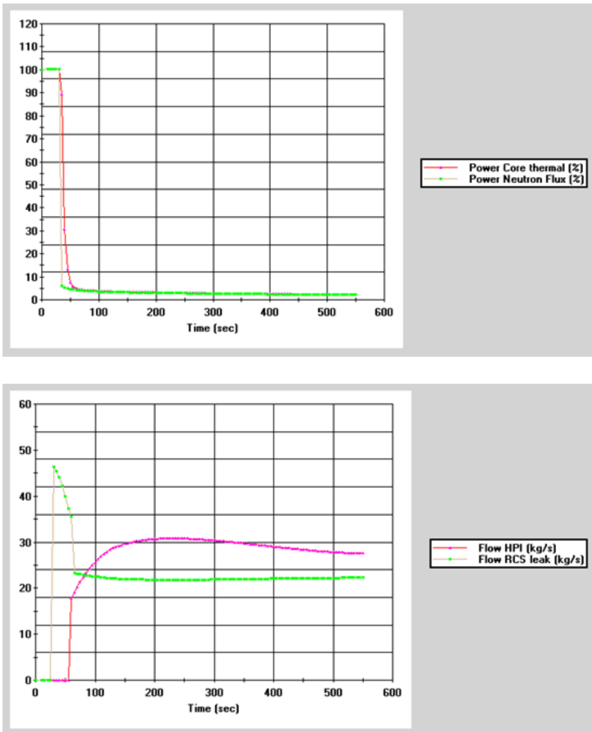

Fig. 3. SMART Loss of Coolant Accident

3. Conclusions

Having conducted some spectrum of normal and accident cases, PCTRAN/SMART has shown to reproduce design features with confidence. It is therefore a viable tool for education and training on the small modular reactor.

REFERENCES

[1] H.C. Kim et al., Safety Analysis of SMART, GENES4/ANP2003: International Conference on Global Environment and Advanced Nuclear Power Plants, Kyoto, Japan, Sep. 15-19, 2003.