Frontiers in Heat Pipes (FHP), 2, 033001 (2011)
DOI: 10.5098/fhp.v2.3.3001

Global Digital Central
ISSN: 2155-658X

Frontiers in Heat Pipes

Available at www.ThermalFluidsCentral.org

NUCLEAR REACTOR MUST NEED HEAT PIPE FOR COOLING

Masataka Mochizuki*, Thang Nguyen, Randeep Singh, Tien Nguyen, Shinichi Sugihara, Koichi Mashiko, Yuji Saito, Vijit Wuttijumnong

R&D Department, Thermal Technology Division, Fujikura Ltd., 1-5-1, Kiba, Koto-ku, Tokyo 135-8512, Japan

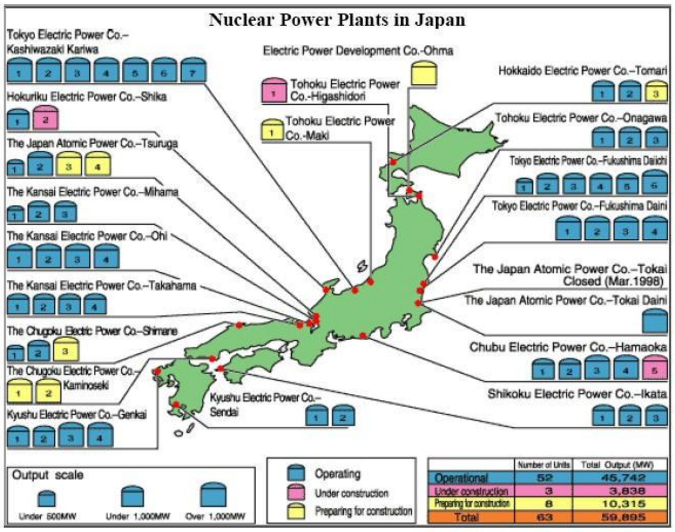
ABSTRACT

In March 11, 2011, a natural disaster of earthquakes and tsunami had caused a serious potential nuclear reactor meltdown in Fukushima, Japan. The problem was lost of electrical power to run the active cooling system for the nuclear reactor in case of emergency nuclear reactor shut down. In this paper, authors present and propose a completely passive cooling system using loop heat pipe for cooling the residual heat of nuclear reactor in case of emergency when the electrical power loss to run the cooling system. The design is focus on the Fukushima No.1 plant which has a capacity of 1,380 MW thermal that capable of producing 460 MW electricity. The system also feature a double wall heat pipe heat exchanger for steam generation in which is more reliable to prevent leakage. The proposed system is passive and is applicable to Boiling Water Reactor (BWR), Pressurized Water Reactor (PWR), and Fast Breeder Reactor (FBR).

Keywords: *boiling water reactor, pressurized water reactor, fast breeder reactor, nuclear power, heat pipe, loop heat pipe.*

1. INTRODUCTION

Figure 1 shows the nuclear power plants distribution in Japan. Currently, Japan has 54 nuclear power plants with a total of 49 GW of electric power production that covers 30% of electricity consumption in Japan. In future, another 19 plants expected to complete by 2017, with additional electric production of 13 GW. All the nuclear power plants are located along the sea coasts as there are readily abundant sea water available for cooling and containment.



	Number of Units	Total Output (MW)
Operational	52	45,742
Under construction	3	3,838
Preparing for construction	8	10,315
Total	63	59,895

Fig. 1 Locations of the nuclear power plants in Japan

The nuclear plant at Fukushima is a Boiling Water Reactor (BWR) type. A schematic example of a BWR is shown in Figure 2. The BWR produces electricity by boiling water, and spinning a turbine with that steam. The nuclear fuel heats water, the water boils and creates steam, the steam then drives turbines that create electricity, and the steam is then cooled and condensed back to water, and the water returns to be heated by the nuclear fuel.

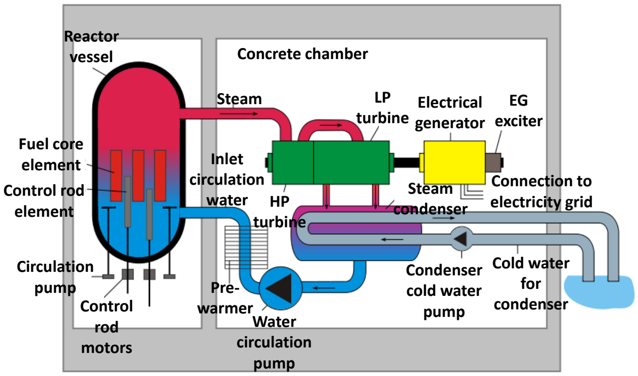


Fig. 2 Boiling Water Reactor (BWR)

The nuclear fuel used in Fukushima nuclear plant is uranium oxide which is a ceramic with a very high melting point of about 2,800 °C. The fuel is manufactured in pellets which are placed in a long tube made of an alloy of zirconium with a failure temperature of 1,200 °C, and sealed tight. This tube is called a fuel rod. These fuel rods are then put together to form assemblies, of which several hundred make up the reactor core. When the earthquake hit, the nuclear reactors will automatically shutdown. Within seconds after the earthquake started, the control rods which are made of boron which are used to absorb the neutrons to control the nuclear fission reaction, had been inserted into the core and the nuclear chain reaction stopped. At this point, the cooling system has to carry away the residual heat, about 7% of the full power heat load under normal operating conditions. The cooling

---

* *Corresponding author. Email : mmotizuk@fujikura.co.jp*

system need to keep the fuel rods below 1,200 °C to prevent the fuel rod melt and caused radioactive fission. If the active water cooling system stop due to loss of electrical power, then the internal temperature and pressure build up caused by the heated steam will cause melt down and explosion.

Figure 3 shows a typical decay heat process. The formulation in the Figure 3 can be used to predict the decay heat output by the reactor fuel after shutdown. It indicated that one second after shutdown, the decay heat produced is between 6 – 7% of heat under normal operating condition, and still continued to produce about 0.5% of heat after a day passed.

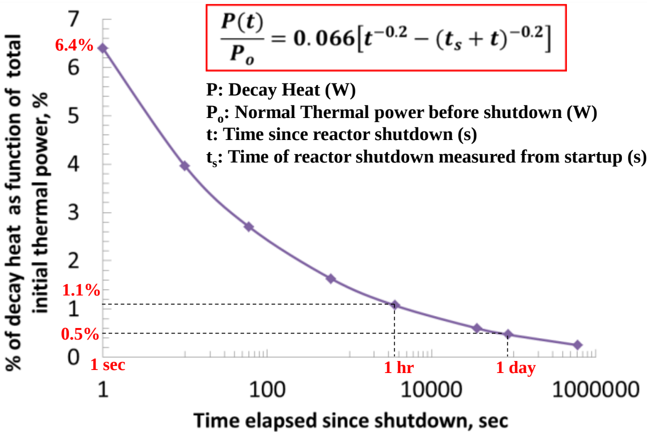


Fig. 3 Decay heat from reactor fuel after shutdown

2. COOLING PROPOSALS

2.1 Overall Emergency Core Cooling System (ECCS)

Figure 4 shows a typical BWR of Fukushima plant. The example analysis given in this paper is for Fukushima plant No. 1 which has a thermal capacity of 1,380 MW with a 460 MW electric power production. In this system the cooling system is active by use of pump to circulate the cooling water to cool the nuclear core. Figure 5 shows a sketch proposed by authors of a passive cooling by use of loop heat pipe for Emergency Core Cooling System (ECCS) (Kaminaga et al, 1988). Figure 6 shows a 3D model of this concept proposal. The concept is using water stored in the emergency cooling water tank by gravity feed to cool the fuel rod at the initial time after the nuclear power plant shut down. Then use loop heat pipe for cooling the decay heat afterwards. Detail designs of each component are given in the following sections.

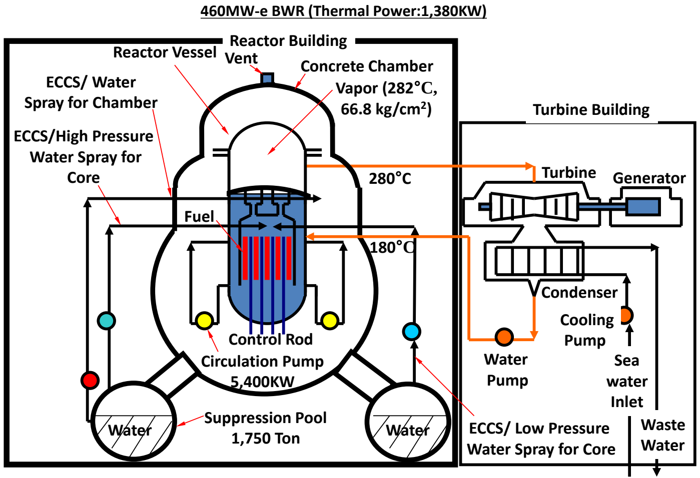


Fig. 4 Fukushima No.1 nuclear power plant

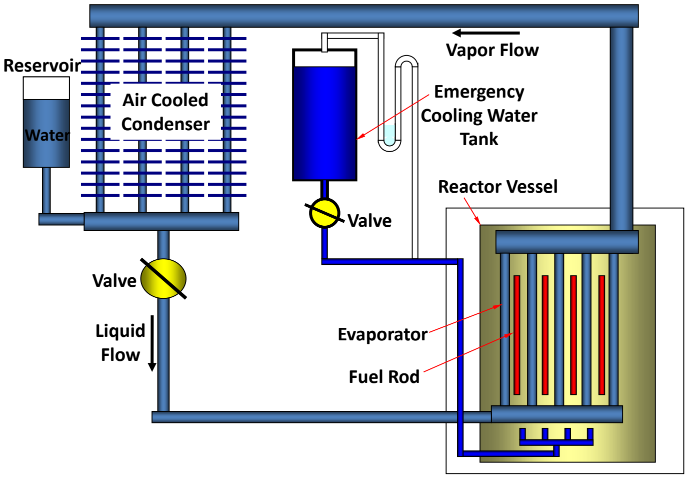


Fig. 5 Schematic of passive cooling system by use of heat pipe for ECCS

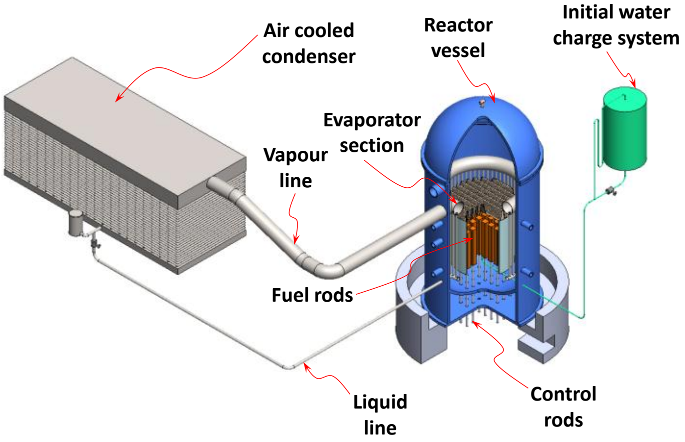


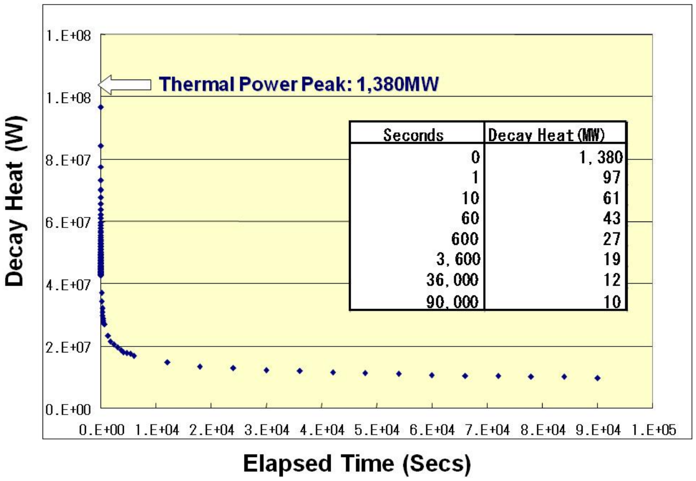
Fig. 6 3D concept of passive cooling system by use of heat pipe for ECCS

2.2 Emergency Water Charge Cooling System

Figure 7 shows the estimation of the decay heat for the Fukushima plant No. 1. It is estimated after the nuclear fission stopped, the decay heat generation about 97 MW at 1 second, and 27 MW at 600 seconds. For the initial 600 seconds, use the water stored in the emergency water tank which is located at elevation for gravity feed the water to cool the fuel rods. The heated water then can be overflow into the suppression pool. The heat estimated from integration of time from 0 to 600 seconds is about 20,100 MJ. The volume of water required can be calculated from equation (1). Assuming that the temperature difference between inlet and outlet of water are 50 and 200 °C respectively, then the volume of water required is approximately 32 m3. After 600 seconds the water cooling can be stopped and the passive loop heat pipe continues cooling the decay heat. As shown in Figure 7, after 600 seconds the decay heat generation becomes about 27 MW which is about only 2% of the maximum thermal power 1,380 MW. With the use of water cooling at the initial time, then the design for the loop heat pipe can be significant smaller in size for the benefit of viable construction cost.

$$Q = \rho V C_p (T_{in} - T_{out}) \qquad (1)$$

Where,
Q = Total heat generation from 0 to 10 minutes = 20,100 MJ
ρ = Water density ~ 1,000 kg/m^3
V = Volume of water (m3)
C_p = Water specific heat ~ 4200 J/kg.K
T_{in} = Water temperature inlet ~ 50 °C
T_{out} = Water temperature outlet ~ 200 °C



Seconds	Decay Heat (MW)
0	1,380
1	97
10	61
60	43
600	27
3,600	19
36,000	12
90,000	10

Fig. 7 Decay heat for Fukushima No.1 nuclear power plant

Figure 8 shows the concept of emergency water charged system. Assuming the cooling water velocity, V is 10 m/s, then the required head, H = $V^2/2g = 10^2/(2 \times 9.8) = 5.1$ m. The 32 m^3 water storage tank can have dimensions, for example internal diameter 3m and height 5m with minimum 4.6 m of water height.

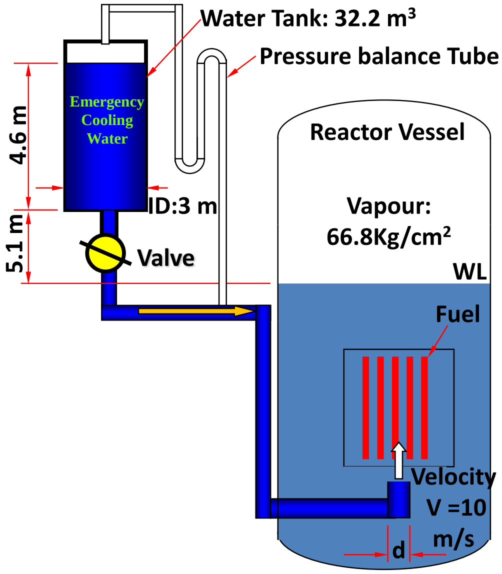


Fig. 8 Conceptual design of emergency water charging system

2.3 Loop Heat Pipe for Cooling Decay Heat

The loop heat pipe is designed for cooling 27 MW. The following sections give detail design about the loop heat pipe evaporator and condenser.

Evaporator Design

Figure 9 shows a schematic inside structure of BWR with loop heat pipe integration, and Figure 10 is a summary of loop heat pipe evaporator design.

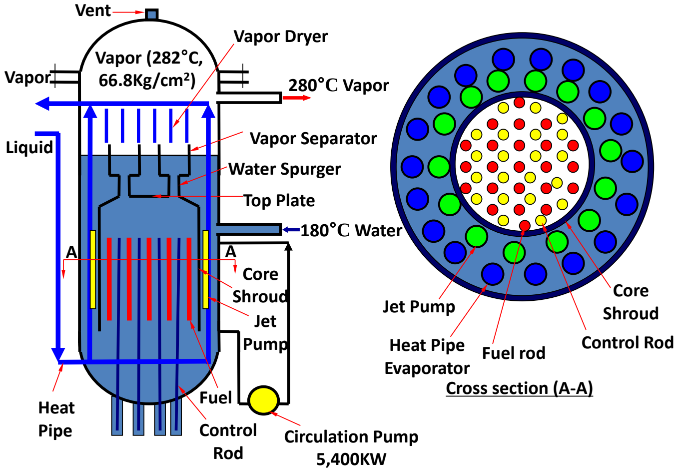
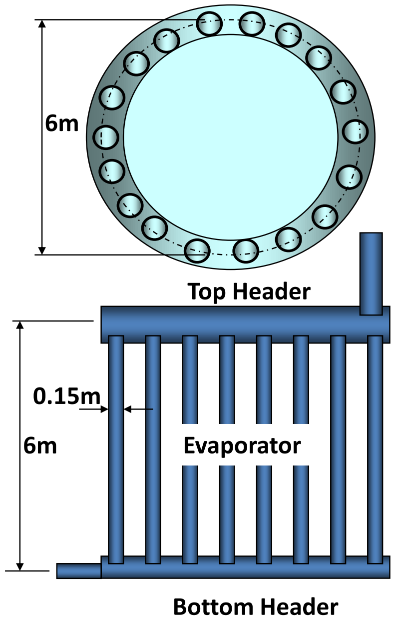


Fig. 9 Schematic of BWR with loop heat pipe integrated inside it

The evaporator consists of 52 pipes of outer diameter 0.15m and 6m long, placed circumference around the fuel core. All the evaporator pipes connected via top and bottom header. Each header is in the form of a ring of outer diameter about 6m. All materials are stainless steel SUS-316L with Ti inside coating.

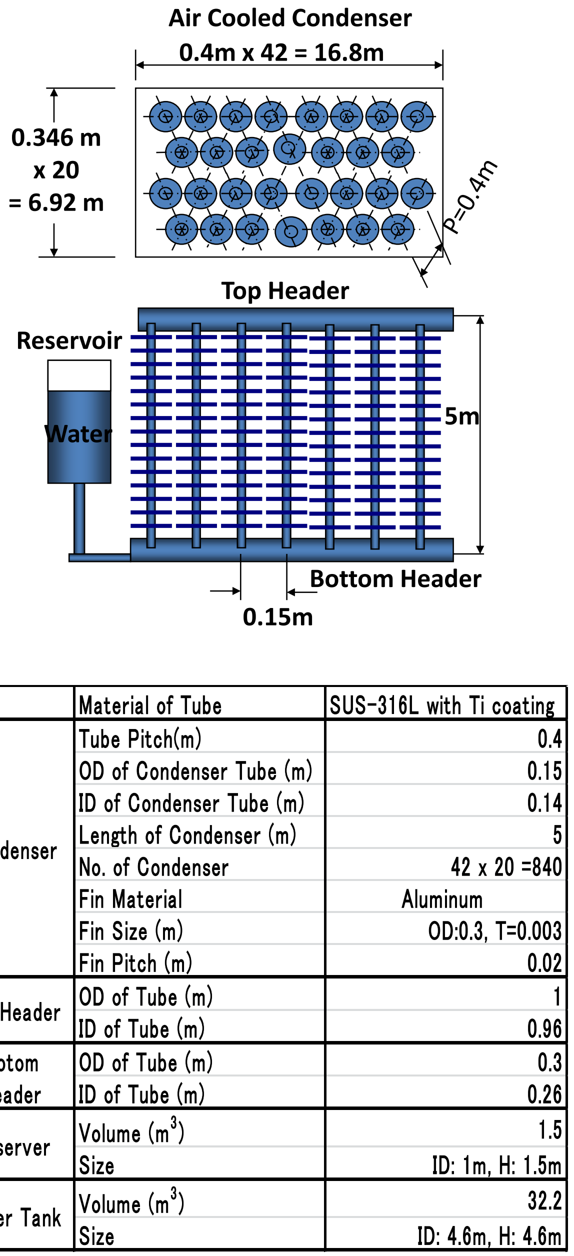


	Material of Tube	SUS-316L with Ti coating
Evaporator	OD of Evaporator Ring (m)	6
	OD of Evaporator Tube (m)	0.15
	ID of Evaporator Tube (m)	0.14
	Length of Evaporator (m)	6
	No. of Evaporator	62
Top Header	OD of Tube (m)	1
	ID of Tube (m)	0.96
Botom Header	OD of Tube (m)	0.3
	ID of Tube (m)	0.26

Fig. 10 Details of loop heat pipe evaporator

Condenser Design

Figure 11 shows a summary of the condenser design. The cooling is by natural convection air cooling. The condenser consists of 840 pipes of outer diameter 0.15m and 5m long. All the pipes connect via top and bottom header. Material of the pipe is stainless steel SUS-316L with Ti inside coating. Each of 840 pipes consists of 250 aluminium fins of outer diameter 0.3m, fin thickness 3mm and pitch 20mm.



	Material of Tube	SUS-316L with Ti coating
Condenser	Tube Pitch(m)	0.4
	OD of Condenser Tube (m)	0.15
	ID of Condenser Tube (m)	0.14
	Length of Condenser (m)	5
	No. of Condenser	42 x 20 =840
	Fin Material	Aluminum
	Fin Size (m)	OD:0.3, T=0.003
	Fin Pitch (m)	0.02
Top Header	OD of Tube (m)	1
	ID of Tube (m)	0.96
Botom Header	OD of Tube (m)	0.3
	ID of Tube (m)	0.26
Reserver	Volume (m^3)	1.5
	Size	ID: 1m, H: 1.5m
Water Tank	Volume (m^3)	32.2
	Size	ID: 4.6m, H: 4.6m

Fig. 11 Details of loop heat pipe condenser

Analysis of heat pipe cooling capability

Figure 12 shows the analysis of the water temperature changes inside the reactor vessel without cooling. Assuming that the water temperature at initial is about 282 °C, it will reach to critical temperature of 374 °C in just 1 hour and continues rising and can reach to 2,500 °C in about 2 days. At this high temperature would expect a catastrophe failure due to melt down of fuel.

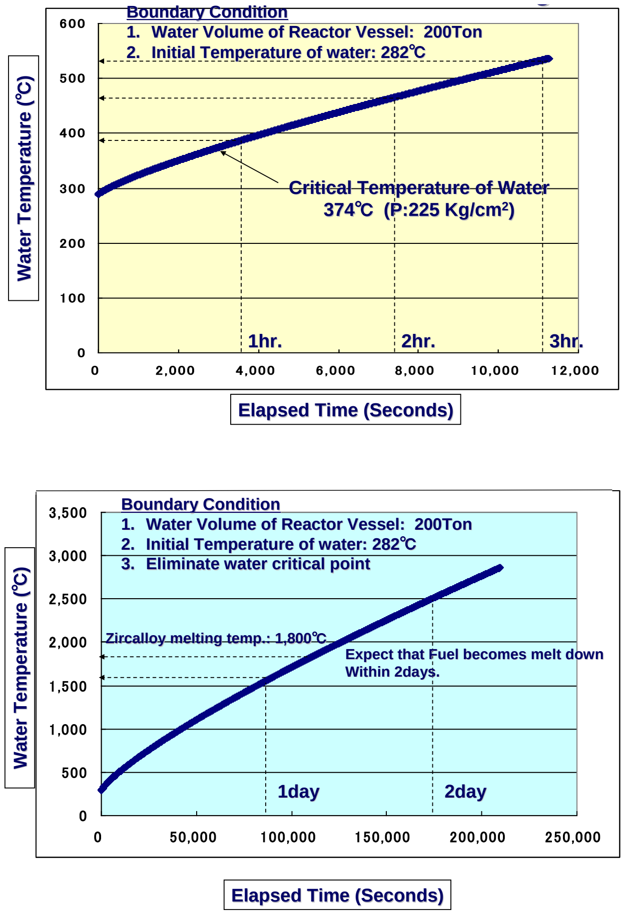


Fig. 12 Water temperature changes inside reactor vessel without cooling

Figure 13 shows the analysis of the water temperature changes inside the reactor vessel with loop heat pipe cooling. The thermal resistance of the loop heat pipe system is approximately 5.77 x 10^{-5} K/W. The calculation shows that the water temperature inside the reactor vessel can reduce to less than 100 °C in less than 14 hours at ambient temperature of 50 °C. If in case use of water charge cooling for the first 600 seconds, then the temperature can reduce to less than 100 °C in less than 6 hours as shown in Figure 14.

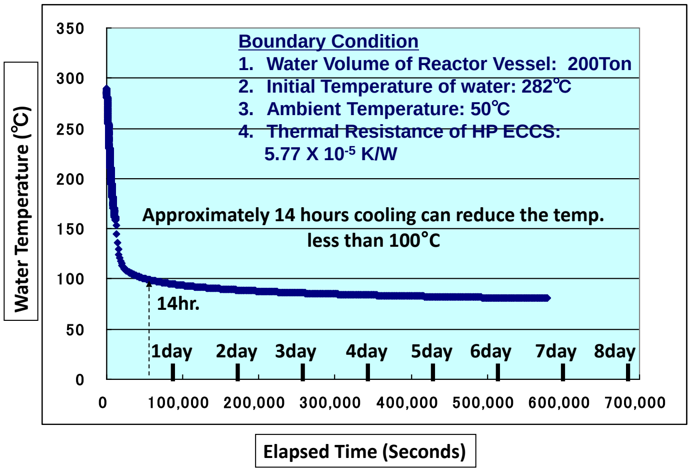


Fig. 13 Water temperature changes inside reactor vessel with loop heat pipe cooling

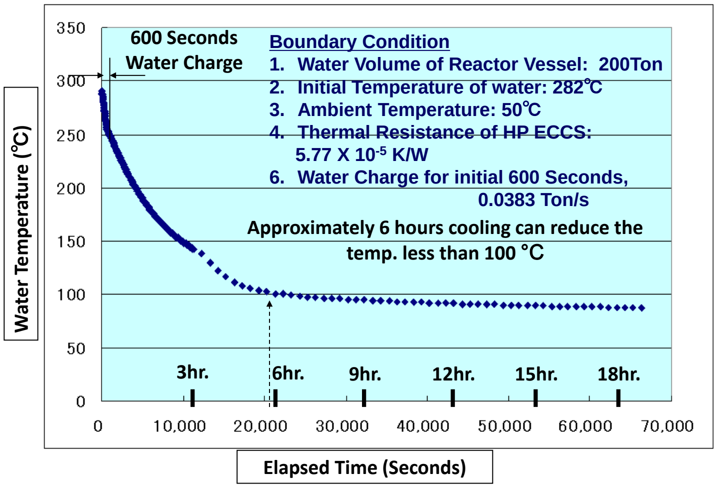


Fig. 14 Water temperature changes inside reactor vessel with initial water charging followed by loop heat pipe cooling

3. NEXT STEP

A prototype of 1/10,000 scale will be built and tested to validate the concept. As mentioned earlier the loop heat pipe is designed for cooling the decay heat of 27 MW, therefore a prototype of 1/10,000 is about 3 kW. Figure 15 shows the prototype concept

The oil tank represents the nuclear reactor vessel. The loop heat pipe evaporator consists of 8 pipes of diameter 25mm and length 0.5m. All the pipes connect via top and bottom header. For the condenser will be cooled by natural air convection. It consists of 5 pipes of diameter 25mm and length 0.6m. Each of condenser pipe has 60 aluminium fins of diameter 120mm, fin thickness 0.5mm and fin gap 10mm.

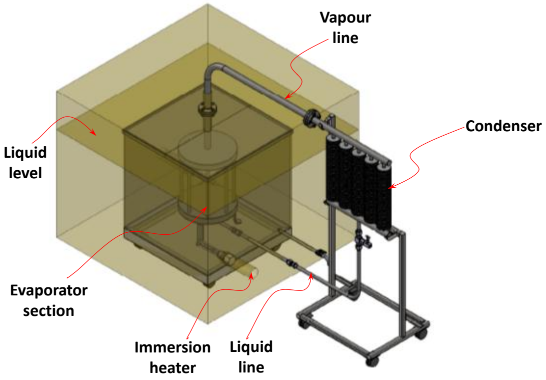


Fig. 15 Loop heat pipe 1/10,000 scale prototype

4. CONCLUSIONS

1. Feasibility study shown that it is possible to use loop heat pipe for cooling the reactor vessel in case of emergency power failure to run the active cooling system. The proposed system can be operated mechanically and completely passive.
2. The cooling capacity of 27 MW Passive Heat Pipe ECCS which is only approximately 2% of Full Thermal Power of Nuclear reactor is economically feasible. The passive cooling system can control water temperature from 282 °C to 160 °C within 3 hours when emergency problem happened.
3. For more safety operation, a 32 m3 initial water charge cooling system by gravity for 600 seconds is recommended.
4. It is recommended 4-5 separated heat pipe system installed for more safety design.

REFERENCES

Kaminaga, F., Okamoto, Y., Keibu, M., Ito, H., Mochizuki, M., Sugihara, S., Application of Heat Pipe to JSPR Safety, Proceeding of Design Feasibility for JSPR, pp. 31-39, UTNL-R0229, December 1988.