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Sodium-Cooled Fast Reactor Helical Coil Steam Generator

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1. Introduction

Helical Coil Steam Generator was chosen as the steam generator design for the 600 MWe sodium-cooled fast reactor being developed by KAERI. The steam generator is helical coil, vertically oriented, sodium-to-water, countercurrent flow, shell-and-tube type unit featuring for a Benson steam cycle once-through sodium heated steam generator application. The steam generator vessel consists of the steam generating helical coil tube bundle and support, feedwater inlet tube assembly, steam outlet tube assembly, sodium inlet distribution assembly and cover gas space. The cover gas space and the inner shroud are used to provide the increased post accident steam venting capability. In order to provide passive protection of the IHX, SG internals were designed, and the results of the design are presented in this paper.

2. Passive protection of IHX[1]

A small SG leak will cause a violent high energy high temperature reaction within the SG. It is necessary to prevent steam from being forced backward into the intermediate heat exchanger(IHX) following a worst case SG leak event in which the steam side isolation and blowdown system fails to operate and terminate the event. To protect the IHX passively SG inner shroud is designed in a manner which prevents the pressure difference between the main sodium inlet and outlet connections from exceeding the level required to force the steam/sodium interface backward along the IHTS hot leg pipe and into the IHX unit under a worst case accident conditions. Failure to terminate the reaction would allow a continuing stream of steam and/or feedwater to enter the SG unit and flow through the broken tubes into the shell of the SG. In this case, the event is not terminated as designed, but continues to allow steam and feedwater to enter the SG through the break side. Since the continuing steam flow will produce a pressure differential between the main sodium inlet and outlet nozzles on its way through the SG tube bundle to the relief system, the main IHTS inlet and outlet nozzles will experience different SG shell side pressures and there will be a tendency for the sodium/steam interface at the inlet nozzle to be pushed backward the IHX. It is important to prevent this reacting interface from progressing back into the IHX, since it employs a large number of small diameter thin wall tubes to transfer heat from the radioactive primary sodium system to the non-radioactive secondary system and under normal conditions it forms both the primary coolant and the containment boundary. Rupturing of these tubes and the subsequent over pressurization of the primary reactor system could lead to a significant radioactive release. To limit the pressure differential in the SG under the assumed worst case accident, the HCSG has been configured to make use of the inactive center region as an alternate flow path for water/steam to be vented from the unit once the sodium has been expelled. To protect the IHX from the ingress of SWR interface due to the pressure differential, the elevation difference between hot and cold leg is to be set to satisfy the following condition;

$$P_1 - P_2 \le \rho g \Delta h$$

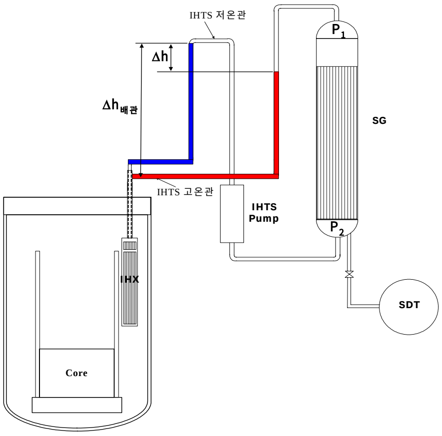

Fig. 1.Sodium levels of IHTS pipes following SWR

3. SG Inner shroud design

It was assumed that the non-safety grade water dump system and the resultant steam and water isolation valves fail to terminate the flow of steam and feedwater to the leak site. It was also assumed that the continuing introduction of steam/water into the shell side of the SG causes all the tubes to rupture. The worst location for a SG tube rupture, from an IHX protection standpoint, is near the top of the tube bundle since tube failures at this location will result in the maximum pressure drop across the steam generator tube bundle and therefore the maximum differential pressure between the sodium inlet and outlet nozzle[1]. Generally flow resistance across the steam generator tube bundle is greater than that of flow through the inner shroud. Therefore it was assumed that all produced steam was vented through the inner shroud to maximize the pressure differential.

$$(P_1 - P_2)_{\max} = f \frac{l_{cyl}}{d_{cyl}} \frac{\dot{m}_{\max}^2}{2\rho A_{cyl}^2}$$

Since tube side pressure is 17.8MPa and shell side pressure is near atmospheric, flow through break area is critical flow. Critical flow rate can be calculated using following equations.

$$h_{stag} = h(P_{steam}, T_{steam}) = stagnation\ \ enthalpy$$

$$\Delta P_{throat} = 0.525 \times P_{steam}$$

$$P_{throat} = P_{steam} - \Delta P_{throat}$$

$$\rho_{throat} = \rho(P_{throat}, h_{stag})$$

$$V_{sonic} = 316.2\sqrt{(\gamma P_{throat} / \rho_{throat})}$$

$$\dot{m}_{crit,tube} = \frac{V_{sonic} D_{tube}^2 \rho_{throat}}{354 \times 3600}$$

Table 1. and Table 2 show SG design conditions and SG design data.

Table 1. SG design conditions

Sodium Hot Leg Temperature [℃]	498
Sodium Cold Leg Temperature [℃]	299
Sodium flow rate [kg/s]	3041
Steam flow rate [kg/s]	344.8
Steam pressure [MPa]	17.8
Steam temperature [℃]	471.2
Feedwater inlet temperature [℃]	215
Thermal duty [MWt]	777.1

Table 2. SG design data

configuration	helical coil
number of tubes	848
tube ID [mm]	20
tube OD [mm]	31.8
overall tube length [m]	118
tube material	2-1/4 CR-1 MO
overall tube heat transfer area [m2]	8992
heat transfer area margin [%]	17
tube bundle transverse pitch	1.8
tube bundle longitudinal pitch	1.5
tube pitch angle	7.33
number tube coil rows	32
helical coin bundle height [m]	13.6
vessel outside diameter [m]	4.9
inner shroud diameter [m]	1.3
SG height [m]	22.7
tube side pressure drop [Kpa]	445
shell side pressure drop [Kpa]	24

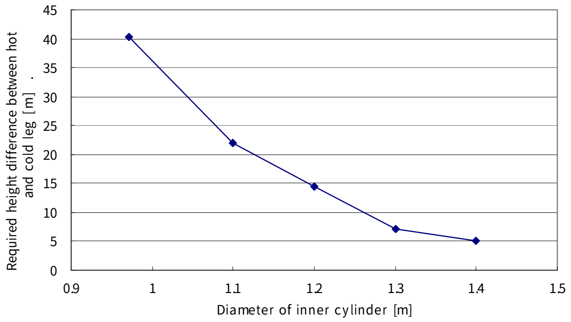

Fig. 2. Effect of inner shroud diameter on required elevation difference

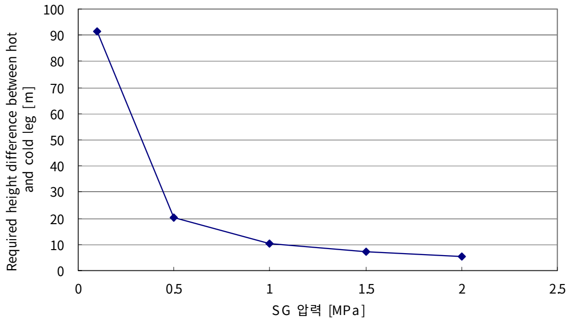

Fig. 3. Effect of SG pressure on required elevation difference

The pressure differential depends on SG pressure condition, hence property change. When SG shell side pressure is 1.5MPa, which is rupture disc design pressure, Fig.2 shows the effect of inner shroud diameter on required elevation difference. In Fig. 2 required elevation difference is about 7m when inner shroud diameter is 1.3m. Fig.3 shows the effect of SG pressure on required elevation difference when inner shroud diameter is 1.3m.

4. Conclusions

HCSG design was configured to provide passive protection of the primary coolant boundary in the IHX for the worst case sodium/water reaction event. When inner shroud diameter is 1.3m, required elevation difference is about 7m.

REFERENCES

[1] C.R. Kakarala and C. E. Boardman, Advanced Liquid Metal Reactor Helical Coil Steam Generator, Proceeding of Thermal Hydraulics of Advanced Heat Exchangers, ASME NE-Vol.5, 1990.

[2] Tae-Ho Lee, 4th generation SFR IHTS components and characteristics evaluation, SFR-FS300-ER-01-2008Rev00, 2008.