Journal of the Korean Nuclear Society
Volume 33, Number 4, pp.423∼440, August, 2001

〈Technical Note〉

Advantages of Acoustic Leak Detection System Development for KALIMER Steam Generators

Kim Tae-Joon, Valery S. Yughay, Hwang Sung-Tai, Jeong Kyung-Chai, and Choi Jong-Hyeun
Korea Atomic Energy Research Institute
150 Dukjin-dong, Yuseung-gu, Daejeon 305-353, Korea
tjkim@kaeri.re.kr

Valery S. Yughay
SSC RF Institute for Physics and Power Engineering
1, Bondarenko sq., Obninsk, Kaluga region, Russia

(Received February 7, 2000)

Abstract

For sodium cooling liquid metal reactors during the last 25 years, it was most important to verify the safety of the steam generator, which absolutely requires a water leak detection system with fine sensitivity and response. This study describes the structure and leak classification of the KALIMER (Korea Advanced Liquid Metal Reactor) steam generator, compared with other classifications, and explains the effects of leak development. The requirements and experimental situations for the development of the KALIMER acoustic leak detection system (KALDS) which detects micro leaks, not intermediate leaks, are introduced. We proposed four frequency bands, 1∼8kHz, 8∼20kHz, 20∼40kHz and 40∼200kHz, split effectively for analyzing the detected acoustic leak signals obtained from the sodium-water reaction model or water model in the mock-up system.

1. Introduction

Sodium-cooled fast reactors have been developed all over the world during the last 50 years. The fast reactors have been developed in 11 countries under the following schemes [1]: Creation and development of a design-experiment base (physical and technological test facilities, computational and verification codes) in Russia, France, UK, USA, Japan, Germany, Italy, India, China, and Korea; Experimental Reactors in Russia, France, UK, USA, Japan, Germany, and India; In design: Italy (PEC), China (CEFR) and Korea (KALIMER); Demonstration NPPS in France, Germany, Japan, India, USA, UK, and Kazakhstan; Commercial NPPS in Russia and France; and in design: EFR, France (Super-Phenix-2), Germany (SNR-2), Japan (DFBR), Russia (BN-800, BN-1600), and USA (CDFR).

During the last 25 years much rich and successful experience with sodium-cooled fast reactor operation has been accumulated. The number of reactors operational in the world is about 280. Today there are three main conventional achievements of sodium-cooled fast reactor technology: Firstly, the fuel cycle, based on mixed oxide fuel and PUREX reprocessing, has become closed in that the plutonium from irradiated fuel has been separated, fabricated into new fuel and recycled to the reactor for further use. It has been established from analyses in various countries that the upper sodium layer above the fissile core region, instead of the upper axial blanket, is a quite efficient design measure to prevent the net reactivity approaching prompt criticality in severe reactor accidents. Secondly, reactor safety experience has been good and sodium-cooled fast reactors have continued to give particularly low radiation doses to operating personnel and low releases of radioactive material to the environment, even in cases of sodium fires and sodium leaks. Thirdly, increased safety is one of the basic requirements slated now all over the world for the operational NPPs and those being designed. The basis for a tightening of the requirements on safety is the emergencies in NPPs in Russia, USA, France, Japan and other countries. These emergencies testify that the existing monitoring systems do not fully provide well-timed detection of distresses arising on an NPP, because of poor sensitivity and response. Simultaneously, numerous malfunctions of emergency systems is operational NPPs take place. These facts also testify to imperfection of the monitoring and emergency systems that are hardwired both to separate parts, and the reactor as a whole.

Thus, the necessity of better diagnostic and control systems in NPP equipment development, directional on sensitization, response and reliability of distress detection in an NPP is obvious.

2. Leak Classification and its Affects in the KALIMER System

2.1. Structure of the KALIMER Steam Generator

The principle arrangement of the primary loop equipment in the KALIMER SG (steam generator) is the integral type (all equipments are placed inside one tank)[2], [11].

The KALIMER SG [3] is a helical coil, vertically oriented, shell-and-tube type heat exchanger with fixed tube sheets. The flow is counter-current, with sodium on the shell side and water/steam on the tube side. Sodium flow enters the SG through the upper inlet nozzles and then flows down through the tube bundle. Feed water enters the steam generator through a tube sheet located on the bottom of the steam generator. The flow restrictors in the tube sheet achieve the desired feed water distribution in the tubes. Water entering the tubes at the bottom of the tube sheet flows through the helical coil tube bundle and exits at the upper tube sheet as superheated steam for normal power operation. The steam generator is designed to withstand normal, upsetting, emergency and faulted operating conditions and its design life is 30 years.

There are two steam generators (l SG / loop) and each is designed to transfer 198.35 MWt and generates 175.5 kg/s of superheated steam at 15.5 MPa and 483.2 °C at the rated full load condition. The conceptual design and outline drawing of the steam generator is shown in Fig. 1. The overall size of the SG is 18.8 m high and 2.8 m in diameter.

The helical coil tube bundle, 6.5m in height and 2.5m in outside diameter, is located between the cylindrical inner and outer shroud and consists of 224 single wall tubes. In the tube bundle, there are 15 different tube coil rows with diameters ranging from 0.9m (1st row) to 2.5m (15th row) with a

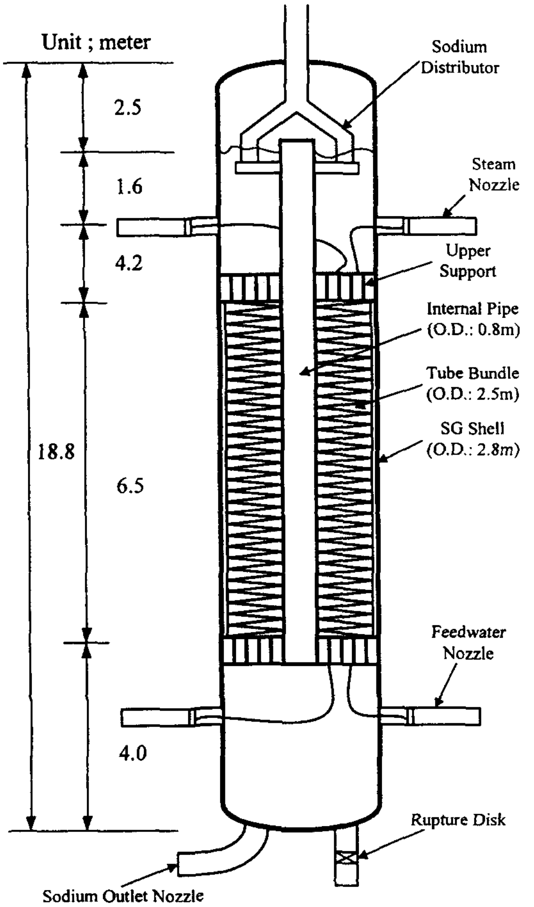

Fig. 1. KALIMER Steam Generator

nominal gap of 30mm between the adjacent coil row of tubes. Each tube is 23mm O.D x 60m long and the tube wall thickness is 3.5 mm. The total outside heat transfer area in the tube bundle is 971 m^2. This SG design includes a 20% additional heat transfer area as a design margin.

2.2. Leak Detection for Water and Steam in the KALIMER SG

The detection of possible leaks of steam-water from the tube to the sodium in the SG shell is done using hydrogen concentration measurement, acoustic detection, and/or measurement of the pressure in the rupture disk piping. The steam generator leak detection system monitors and alarms of water or steam leaks in the KALIMER SG and identifies the faulted steam generator [4].

The Small leak (<10g/s) detection subsystem uses measurement of the hydrogen concentration in the liquid sodium stream as a method of leak detection. The leaking of water/steam into the sodium stream increases the hydrogen and oxygen concentration in the sodium. The measurement of hydrogen in the sodium is accomplished by allowing hydrogen to diffuse through a thin nickel membrane, one side of which has a high vacuum held by an ion pump. These detector modules are installed on the main sodium piping at the steam generator outlet and cover gas space. The purpose of this is the early detection of a water/steam leak into the sodium.

In order to have adequate coverage, redundant detectors are provided to accommodate detector malfunctions during operation. A minimum of two operational hydrogen meters are installed to ensure leak detection coverage at all times.

Intermediate leaks (10 ~ 1000g/s) generally continue for about 30 seconds and the leak can be identified within 3 seconds by the acoustic detection system, after which steam generator protective actions are initiated. The acoustic system provides leak detection reliability and diversity in the overlapping region.

Large leaks (above 1 kg/s) generally continue for several seconds and cause the rupture disk to burst. These leaks can be found by detecting the pressure of sodium or the sodium water reaction product in the pipe region between the two rupture disks serially installed at the bottom of the steam generator.

2.3. Leak Classification of Water/Steam into Sodium

The size of initial defects, through which the

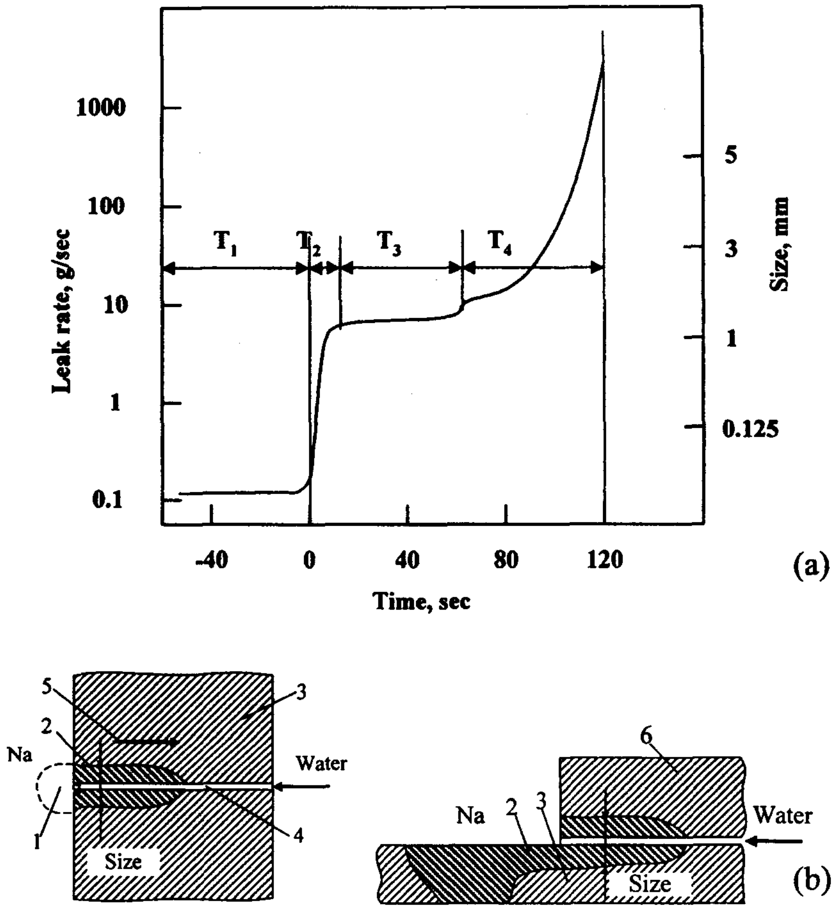

Fig. 2. Representative Change of Water Discharge in Sodium in Time (a) and Scheme of Destruction Processes of Self-Development of Leakage from Defects in a Tube Wall (b) and from a Defect at a Place of Seal of a Tube in a Tube Plate :
1. Reactions Zone; 2. Destruction Zone; 3. Tube Wall; 4. Flow-out Initial Channel; 5. Direction of Destruction Front; 6. Tube Plate

flow of water-steam into sodium starts, is minimal. In the final stage of SG operating time the probability of leaks increases, and it is necessary to expect, consequently, that the initial water volume reacted with sodium, will increase. Thus, the outward flow of water in the sodium through defects is probable, the size of which appears to be several lobes of millimeter, and only exceptional cases reach the equivalent size of 1 mm, i.e. the value of an initial leak of water into the sodium will be, as a rule, tenth and even 100-th lobes of a gram per second and will only in infrequent, exceptional cases reach the value of one gram per second or greater. One of the main features of water-steam into the sodium out-flow is the self-development of a defect resulting in the subsequent ascending of water discharge and the destruction of tubes adjacent to the defective one.

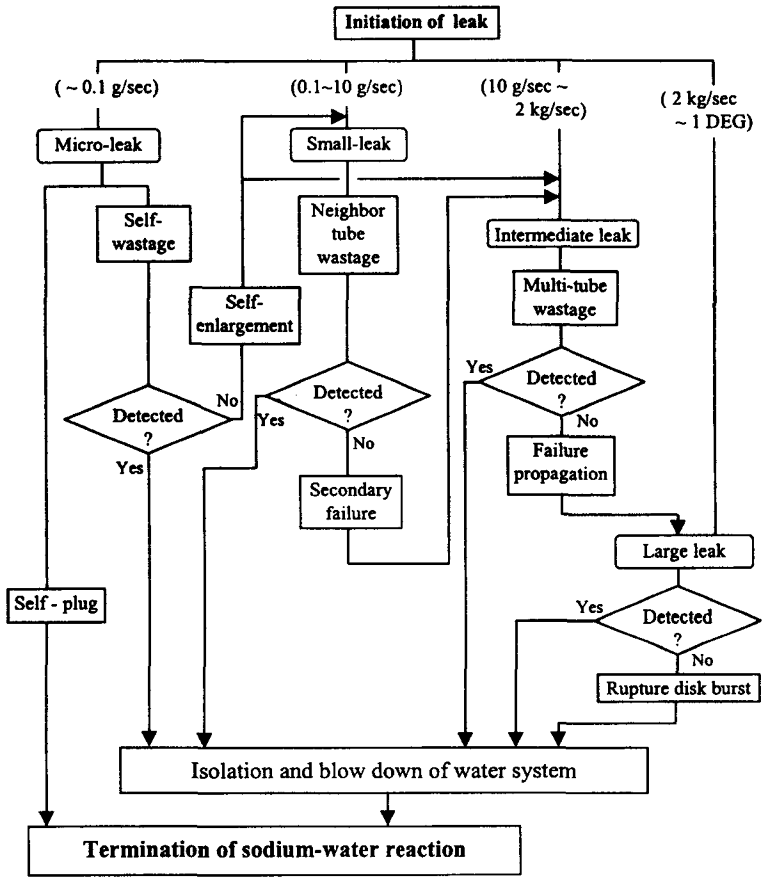

Fig. 3. Detection Procedures for the Termination of Sodium-Water Reaction

A representative out-flow of water into sodium in time is submitted [5] in Fig. 2.

As shown in Fig. 2, all of the times of water-steam into the sodium out-flow can be sectioned as follows. For T_1, the flow rate is saved at an average level, the reduction and even the stop of out-flow on continuous time with subsequent spontaneous recovery is possible. For T_2, the final stage of leak self-development, after some seconds and for a short time, water out-flow increases. As a rule, the intensive spray effect on tubes adjacent to the defective one, starts this time. For T_3, formed as a result of leak self-development, the defect descends the out-flow of water with large practically by a constant flow rate and, finally, the tubes adjacent to the defective tube will be damaged. For T_4, an increase of the out-flow is conditioned by the occurrence and increase of secondary leaks in heat-transfer tubes.

Depending on the consequences of a water in sodium leak for the thermo-hydraulic parameters of a sodium loop and the condition of the steam generator, there are two main kinds of leaks: with and without neighboring tube damage, which do or do not lead to a secondary leak.

The behavior of a leak and opportunities for detection depend on its size. These are outlined in Fig. 3. It is convenient to define them in four classes as follows [6].

Micro leak(< 0.1 g/s) : this is a leak which is too small to be detected. For example, it might be due to an inter-granular crack in an imperfect weld. Reaction products form so slowly that they do not damage other tubes.

Small leak(0.1 ~ 50 g/s) : this is a leak which produces a reacting jet capable of impinging on the adjacent tubes and damaging them. It might be due to a fatigue crack 1 cm or more in length in a tube.

Intermediate leak(0.05 ~ 2 kg/s) : this is a leak which engulfs many other tubes in reaction products and produces a significant excess of pressure in the secondary circuit. It might be caused by a complete failure of a single tube so that steam flows unimpeded from both of the broken ends (this is sometimes known as a "Double-Ended Guillotine Fracture", DEGF). However, if water rather than steam flows from a DEGF, flow rates of 10 kg/s may be possible.

Large leak(>2 kg/s) : this is a leak, which pressurizes the whole secondary circuit and expels the majority of the sodium from the SG affected. It might be caused by the failure of several tubes.

The corrosion rate is higher in ferrite than austenitic steels and higher still in Incolloy. The flow rate through a micro leak is so small that the corrosion products are not swept away, but remain in place. In some cases this has been observed to seal the leak so that the flow-out of water or reaction products to the sodium stops. However, the leak may still be active in the sense that water and sodium continue to diffuse through the corrosion-product plug, and interact to form sodium hydroxide which then attacks the metal, so that the plug of corrosion products grows. Eventually it is no longer able to support the pressure in the tube and blows out, leaving a hole up to 1 mm in diameter. The result may be a small leak, with a flow rate of 10 g/s or more, appearing instantaneously with no detectable warning. The incubation period, in Fig. 4 [16], from the formation of a micro leak to the sudden appearance of a small leak may be several days or weeks.

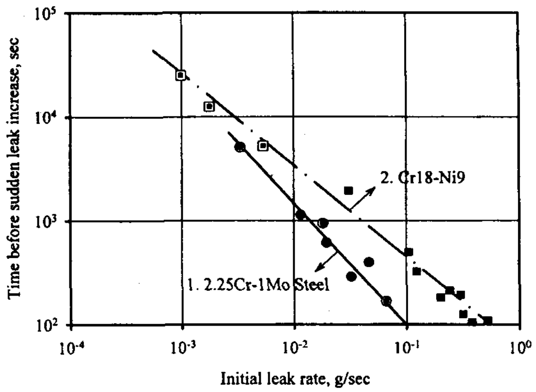

Fig. 4. DTime Period from Leak Beginning until Sudden Leak Increase of Water Leak Rate(Sodium Temperature 450℃, Wall Thickness 2.5); 1. 2.25Cr 1Mo Steel, 2. X18H9 Steel(Cr18 Ni9)

A small leak grows from a combination of corrosion and erosion. Although a high velocity jet of steam or water blows out of the leak, there is back-diffusion of sodium around the jet into the hole, where it reacts with water and corrodes the metal. Grains are loosened by inter-granular corrosion and swept away by the jet.

2.4. Attenuation and Absorption Effects of Leak Noise

The interaction of leak noise and hydrogen bubbles in sodium is accompanied by the dissipation of three types of energy [10] that are thermal losses due to bubble warming and heat transfer to sodium. When the volume of the bubble changes under the sound wave influence (δ_T), the emission losses are due to the diffusion of some part of the sound energy by the disturbing bubble as a spherical radiator (δ_R), and the viscosity losses are due to sodium stream formation around the oscillating hydrogen bubbles in the sodium (δ_V). Consequently, the total attenuation coefficient will be equal to the summation of these three components, $\delta_T = \delta_T + \delta_V + \delta_R$. For each component, the viscosity attenuation coefficient is:

$$\delta_V = \frac{8\pi\mu_{Na}}{3\gamma P_o} f_o \sqrt{\frac{d}{b}} \tag{1}$$

The radiation attenuation coefficient is

$$\delta_R = \frac{2\pi R_o}{C_{Na}}, \tag{2}$$

where C_{Na} is the sound velocity in sodium.
The thermal attenuation coefficient is:

$$\delta_T = 2\cdot\left\{\frac{\left[\left(\frac{16}{9(\gamma-1)^2}\cdot\frac{F\cdot b}{f_p}-3\right)^{1/2}-\frac{3\gamma-1}{3(\gamma-1)}\right]}{\frac{16}{9(\gamma-1)^2}\cdot\frac{F\cdot b}{f_p}-4}\right\} \tag{3}$$

In that time, the frequency of the hydrogen bubble oscillation is:

$$f_o = \frac{1}{2\pi R_o}\sqrt{\frac{3\gamma P_o}{p_{Na}}} \tag{4}$$

The surface tension forces account is:

$$b = 1 + \frac{2\sigma}{P_o R_o} - \frac{2\sigma}{3P_o R_o \gamma} \tag{5}$$

The deviation of the hydrogen compression process in the bubbles from adiabatic is:

$$d = 1 + \frac{3(\gamma-1)}{2\hat{O}_1 R_o}\left[1 + \frac{3(\gamma-1)}{2\hat{O}_1 R_o}\right] \tag{6}$$

Using

$$\hat{O}_1 R_o = \sqrt{\frac{F}{f_r}} \tag{7}$$

$$F = \frac{3\gamma P_o b}{4\pi \rho_{Na} a_k} \tag{8}$$

$$f_r = f_o\sqrt{\frac{b}{d}} \tag{9}$$

f_r is the resonance frequency of hydrogen bubbles, and f_o is the frequency of hydrogen bubbles.

From assumptions of the resonant mechanism of sound absorption of the hydrogen bubbles in sodium and the small contents of gaseous hydrogen in sodium, when the hydrogen bubbles sections are not blocked, the cross sections of the extinction of leak noise on hydrogen bubbles in sodium could be calculated as follows;
The effective cross section [12] of extinction is

$$\sigma_e = \sigma_a + \sigma_s$$

$$\sigma_e = \frac{4\pi R_o^2\left(\frac{\delta}{\eta}\right)}{\left(\frac{f_o^2}{f^2}-1\right)^2+\delta^2}, \tag{10}$$

where $\eta = \frac{2\pi R_0}{\lambda}$ is the ratio of bubble circle length to the length of a wave.
For the cross section of absorption,

$$\sigma_a = \frac{4\pi R_o^2\left(\frac{\delta}{\eta}-1\right)}{\left(\frac{f_o^2}{f^2}-1\right)^2+\delta^2} \tag{11}$$

For the cross section of dispersion,

$$\sigma_s = \frac{4\pi R_o^2}{\left(\frac{f_o^2}{f^2}-1\right)^2+\delta^2} \tag{12}$$

The penetration coefficient [13] of water boiling noise through the tube wall into sodium can be calculated by

$$K = \frac{4\rho_3 c_3 \rho_1 c_1}{(\rho_3 c_3 + \rho_1 c_1)^2 \cos^2 n_2 l_2 + \left(\rho_2 c_2 + \frac{\rho_3 c_3 \rho_1 c_1}{\rho_2 c_2}\right)^2 \sin^2 n_2 l_2}, \tag{13}$$

where $\rho_{1,2,3}$ are the density of water, steel, and sodium in that order, $c_{1,2,3}$ are the sound velocity of water, steel, and sodium in that order, the parameter is $n_2 = 2\pi/\lambda$ and λ is the length of the sound wave.

The sound velocity [14] in the water-steam mixture is

$$\frac{1}{c_s^2}=\frac{\alpha}{c_s^2}-\frac{\alpha(1-\alpha)}{c_s^2}\left(1-\frac{\rho_s c_s^2}{\rho_w c_w^2}\right)+\frac{1-\alpha}{c_w^2}-\frac{\alpha(1-\alpha)}{c_w^2}+\frac{\alpha(1-\alpha)\rho_w}{P}, \tag{14}$$

where α is the ratio of steam to volume, P is the steam pressure, and the density of the water-steam mixture is $\rho_m = \rho_s\alpha + \rho_w(1-\alpha)$. This formula is used for the estimation of water-steam mixture as a ρ_3 in Eq. (13).

3. Development of a KALIMER Acoustic Leak Detection System

3.1. Types of Acoustic Leak Detection Systems

From the point of view of leak detection in the SG we can distinguish two types of diagnostic systems, founded on passive and active acoustic methods.

In the case of an active acoustic method the appearance of hydrogen bubbles, which have arisen as a result of reacting water-steam within the sodium, a permanently "sounded" volume of circulating sodium is controlled. This local, permanently irradiated by ultrasonic oscillations in the controlled volume of circulating sodium, is as a rule on an outlet of sodium flow from the SG. Thus the influence of background noise from the SG on the detection of hydrogen bubbles in sodium is practically insignificant. The main problem with the active method is the existence of cover gas bubbles in the controlled sodium flow, which one can recognize as hydrogen bubbles. An active system is unable to distinguish bubbles of protective gas from bubbles of hydrogen, which decreases the reliability of leak detection in the SG.

In the case of a passive detection system the appearance of noise is bound to the reacting of water-steam with the circulating sodium, the noise of the out-flow of a steam-water spray is controlled in all volumes of the SG, and also the concomitant acoustic effects, bound to the appearance of gaseous hydrogen in the sodium, are controlled. Thus the main problem is the detection of a gentle noise micro leak from the potent background noise of the SG. It is necessary to note that to the present time the capability of detecting the noise of a micro leakage (less than 1 g/s), from the potent noise of the industrial steam generator at a ratio S\N = −20 dB, has been successfully demonstrated.

3.2. Structure of the Acoustic Leak Detection System

In essence the KALDS (KALIMER acoustic leak detection system) includes three parts, hardware for reception and measurement of a leak jet noise and of water/steam - sodium reaction noises, software for acoustic signal processing, and software for decision making about leak availability.

The hardware for the reception and measurement of leak noise includes the following: acoustic sensors, pre-amplifiers, amplifiers, cable lines, and switchboards (multi-plexer).

The software for processing acoustic signals includes the following: filtration of the signals, formation of an effective frequency range, spectral analysis of acoustic signal, and adaptive filtrating of the acoustic signal.

The software for decision making about leak availability includes the following: a neural network, an algorithm of decision marking about the possibility of a leak with allowance for indications from the hydrogen detection system.

It is necessary to note that the contents of all three parts of the KALDS can be varied and should correspond to the specific design features of each separate steam generator. It in turn demands the personal experimental substantiation of both the separate parts of the KALDS, and the system as a whole.

3.3. Experimental Status of KALIMER Acoustic Leak Detection System Development

3.3.1. Selection of Acoustic Sensor

It is now possible to state that in different countries experience with the successful application of different types of acoustic sensors for leak noise detection at a sodium temperature of 200 ~500℃, has been accumulated both in sodium test facility conditions and on an industrial steam generator. From the examples [7] in tables 1, 2, and 3, where the characteristics of acoustic sensors are submitted, we can determine which one should be used in the ALDS.

Therefore, for the KALDS the development of a special acoustic sensor is not required, and the experimental substantiation of the usage of selected acoustic sensors is necessary.

3.3.2. Experimental Investigation of Water-Steam Leak Noise

The acoustic measurements of leak noise were first carried out for an intermediate leak. For those conditions a hydrogen detection system is not capable of supplying well-timed detection to avoid a secondary leak and the destruction of adjacent tubes. The experiments on an ASB loop have confirmed the efficiency of the acoustic method of intermediate leak detection.

From the ASB experiments these important general results [8] have been determined: All primary leaks (0.3 ~ 1 mm diameter), leak enlargements, secondary leaks, overheating defects and noisy control procedures were clearly detected by all acoustic sensors. In a low noise system a passive acoustic leak detection system seems to be fast and reliable enough (without using sophisticated data processing techniques) to initiate measures for preventing leak propagation.

Measurements of micro-leak noises (0.02 ~ 0.8 g/s) in circulating sodium at a sodium temperature of 350℃ ~ 500℃ at a distance of 1650 mm were executed in the IPPE and have confirmed prospects of the passive acoustic method for micro-leak detection in an industrial steam generator.

Magnetic recording of acoustic noises of micro-leaks registered in these experiments have formed the basis for successful development of different methods of allocation and the separation of a micro-leak acoustic signal (the IPPE data) from the background noise of an industrial steam generator (the PFR data, the SPhx data) in the countries participating in the IAEA coordinated research program [9].

The outcomes of this research can be formulated as follows: The conditions of acoustic measurements in a module of the SG such as BN-600 for micro-leak detection in a tube bundle of the SG have been analyzed; The effective range of frequencies for micro-leak detection in a tube bundle of the SG have been determined. A reasonably effective frequency range is the frequency band 1 ~ 200 kHz. Splitting an effective range of frequencies into 4 sub-bands 1 ~8 kHz, 8 ~ 20 kHz, 20 ~ 40 kHz, 40 ~200 kHz is expedient. This separation has its foundation from the peculiarities of background noises in a steam generator unit. According to acoustic measurement procedures, in the frequency range of 1 ~8 kHz the level of background noise is fairly

Table 1. AE Sensors Possible with the Application of Acoustic Leak Detection

Manufacture and model	DECI (USA) SE1000-HI	DECI (USA) SE9125-M	PAC (USA) S9215	PAC (USA) R15IU	IPPE-VNIIEF (Russia)
Peak sensitivity	~72 dB in 1V/㎛ (~900 mV/g at < 2 kHz)	<80 dB in 1V/μ bar(or 58 dB 1V/㎛ at 130 kHz)	52 dB in 1 V/m/s at ~50 kHz (<-80 dB in 1V/μ bar)	~50 dB in 1 V/m/s (-74 dB in 1V/μ bar)	~60 dB inV/m/s at 100 kHz
Operational frequency band	100~400000 Hz (flat <2 kHz, accelerometer mode)	100~1000 kHz	50~650 kHz (50~1000 kHz)	10~200 kHz	50~250 kHz (up to 1 MHz with peamplifier)
Operational temperature	< 70℃	<100℃	<540℃	<85℃	<250℃
Dimensions	ø 20x23 mm	ø 20x16 mm	ø 20x20 mm	ø 28x40 mm	ø 20x~40 mm
Case material and weight	Aluminium standard (21 g). Stainless steel available.	Aluminium standard (12 g). Stainless steel available.	Inconel 600	Stainless steel (Face - ceramic)	Stainless steel
Grounding	Case isolated with ceramic wear	Case isolated with ceramic wear	Case grounded and isolated	Case grounded and isolated	Case isolated
Integrated preamplifier	Yes. Line drive preamplifier for long cables. DECI 1000J module and cable MB1 are required to supply +15 V.	No. DECI 400 (gain 40 dB, dynamic range 74 dB, out 50 (Ω) outer preamplifier (with high-pass filter) is necessary	No.	Yes. 40 dB gain 300 m cables	No preamplifier required. <150 m cables
Sensor circuit	Single ended	Single ended	Single ended. Differential configuration also available (D9215)	Single ended.	Single ended
Comments	Attachment to steel waveguide is provided.	Attachment to steel waveguide is provided.	High temperature sensor	Under water sensor	The sensor is manufactured being attached to stainless steel waveguide.

stable. In the frequency range of 8 ~ 20 kHz the background noise level begins to decrease. The influence of the tube bundle diffraction effect in the frequency range of 20 ~ 40 kHz is expected. In the frequency range of 40 ~ 200 kHz the background noise level is low.

The influence of gaseous hydrogen in sodium on attenuation of micro-leak noise is determined. In

Table 2. Immersible Sensors Possible with the Application of Acoustic Leak Detection

Manufacture	CEA (France)	AEA-T (UK)	Russia *
Operational frequency band	< ~5 MHz	0.5 ~ 5 MHz	2 - 150000 Hz (flat) first resonance ~250 kHz
Operational temperature	< 600℃	< 600℃	< 700℃
Sodium pressure	40 bar	-	<150 bar
Dimensions	~ ø 32 mm	-	ø 10x45 mm
Thermal shock	20 C/second	-	-
Comments	Long time successful operation in sodium	-	Preamplifier is supplied

*It is a high sensitivity dynamic pressure sensor, basic principles of which could be used for elaboration of acoustic sensors for the SG sodium-water conditions.

Table 3. Accelerometers Possible with the Application of Acoustic Leak Detection

Manufacture and model	Charge sensitivity	Transverse sensitivity	Temperature range and deviation	Frequency range and resonance frequency	Dimensions and weight	Comments
Endevco (USA) 2276	10 pC/g	<3% (<1% on special order)	≤482℃ 15 %	1 ~ 5000 Hz (+/- 5%)* 27000 Hz	ø 15.7x 25.4 mm, 30 g	Signal (ground) connected to case. Hermetically sealed. Inconel case. Designed for NPP.
Endevco 6237M	10 pC/g	<5%	≤650℃	2 ~ 5000 Hz (+/- 10 %)* 11000 Hz	ø 14.2x 24.1 mm, 30 g	Signal isolated from case. Non hermetic. Thermal shock: 38℃ per minute. Long MTBF.
Endevco 2273AM1	10 pC/g	<3%	≤399℃	20 ~ 5000 Hz (+/- 5%)* 27000 Hz	ø 15.7x 22.9 mm, 32 g	Signal isolated from case Hermetically sealed Inconel case Designed for NNP acoustic monitoring
Bruel&Kjaer (Denmark) 4391	9.8+/-0.2 pC/g	<4%	≤180℃	0.2 ~ 8700 Hz (5%)* 40000 Hz	ø 15 x 31.2 mm, 16 g	Signal/case >100 MΩ Hermetically sealed Titanium case Designed for industrial (wet, dusty and explosive) conditions.
Global Test (Russia) AP63	10 pC/g	<5%	≤400℃	2 ~ 7000 Hz (+/- 2.8 %)*	98 g	Signal/case 1000 MΩ Stainless steel case

* In the indicated frequency range the specified sensitivity lies within the defined (in %) amplitude tolerance band

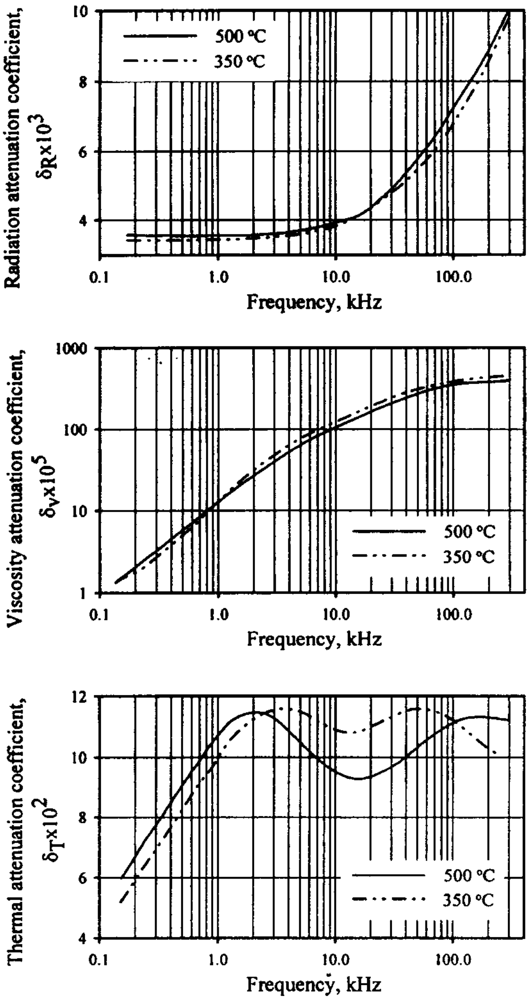

Fig. 5. Thermal, Viscosity and Radiation Attenuation of Sound on Hydrogen Bubbles in Sodium

Fig. 5 [15], the outcome of calculations of attenuation coefficients of the leak noise of hydrogen bubbles in sodium at temperatures of 350℃ and 500℃ is presented.

All cases of micro-leaks (0.05~0.8 g/s) at sodium temperature of 350℃~500℃ at a distance of 1650 mm were registered and the acoustic spectra of noise power were measured. These measurements are presented in Figs. 6 and

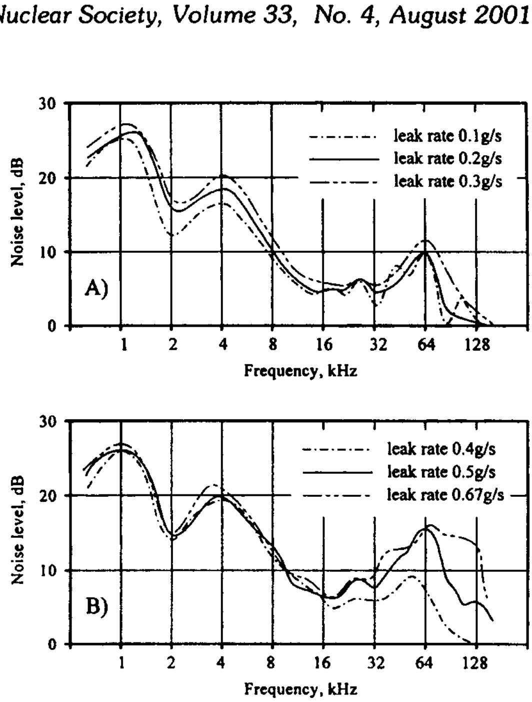

Fig. 6. Thermal, Viscosity and Radiation Attenuation of Sound on Hydrogen Bubbles in Sodium

7. In Fig. 8 [15], the representative micro-leak noise spectra at different sodium temperatures are presensted.

The outcome of this research also testifies to the prospects of the application of a passive acoustic system for the detection of not only intermediate leaks, but also for the detection of micro leaks. It will allow the improvement of reliable leak detection and, consequently, an increase in the safety of the SG and NPP as a whole.

3.4. Study of Background Noise in the Steam Generator

The main sources of background noise in an industrial steam generator are the circulation of sodium coolant outside the steam generator' s tube bundle, the water boiling process inside of the tubes in the SG tube bundle, and the motion of the steam-water mixture inside the SG.

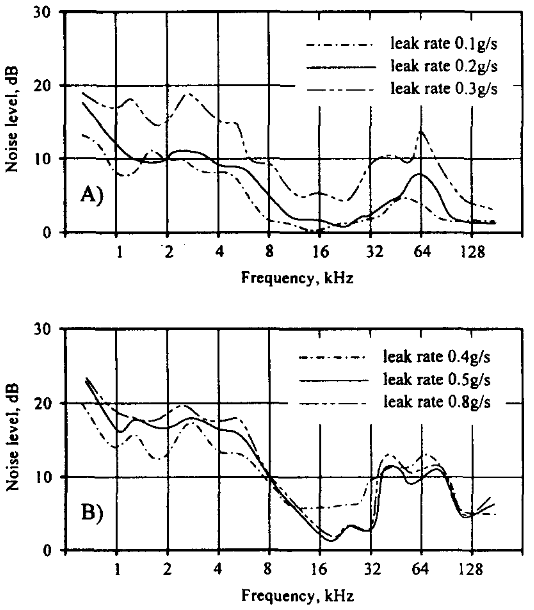

Fig. 7. Leak Noise Spectra at a Sodium Temperature of 500℃, Distance 1650mm

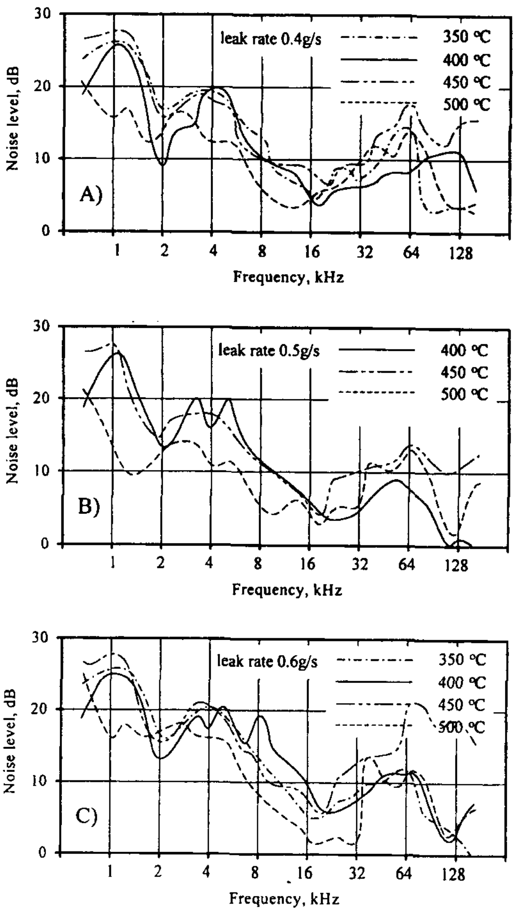

Fig. 8. Leak Noise Spectra at Different Sodium Temperature of 500℃, Distance 1650mm

The main prevailing source of background noise inside the SG is the noise of water boiling. When the boiling noise penetrates into the sodium, the tube wall is selecting a frequency as a mechanical filter. When the sonic wave penetrates from the water-steam side into the sodium side through the tube wall, part of its acoustic energy will be reflected on the regions boundary. Primordial influence on the part of the penetrated sonic wave will be produced by the ratio of impedance in the water-steam, steel and sodium mediums. From the calculation results on boiling noise power attenuation in the BN-600 evaporator module, it is determined that boiling water noise attenuation is minimum at the tube inlet, and maximum attenuation corresponds to the steam quality. The frequency dependence of water boiling noise attenuation has two characteristic areas. In regions of low frequency to 8 kHz the attenuation of boiling noise is practically a constant value, then, in accordance with frequency growth in the ultrasonic region, boiling noise attenuates, in the ultrasonic region the rate of boiling noise attenuation is approximately 5 dB per octave.

As the volume of steam quality grows, identical kinds of frequency dependencies fill in the space between the curves, according to the conditions of the evaporator and super heater modules.

The background noise measurements in the evaporator and super heater modules of the BN-600 in a normal mode of power results are as follows:

- The decreased level of frequencies in the ultrasonic region is observed, which resulted from the calculation results. In the frequency range of 30~200 kHz the background noise is stable and is 15~20 dB lower than the level of background noise in the frequency range of 2~20 kHz.
- The last circumstance creates optimistic preconditions for the detection of water-steam leaks into sodium in the ultrasonic frequency range.

3.5. Separation of Micro Leak Noise from Background Noise for an Industrial Steam Generator

The development of leak noise separation methods from background noise for an industrial steam generator has been implemented in all countries, according to the BN reactor development programs of these countries. The most considerable success was reached under the framework of the IAEA coordinated research program in 1990~ 1995. This method successfully demonstrates the high probability of separating small (leak noise data for a leak rate of 0.1 to 1.0 g/s offered by the IPPE, Russia) and intermediate (leak noise data for leak rate of 1.8 g/s and 3.8 g/s from the ASB loop, Bensberg, Germany) leak noises from the background noise of the SG of the PFR.

From the results obtained by testing the various analysis techniques for acoustic leak detection on synthesized data and on the PFR background noise data, the following conclusions were made [9]:

- Leak signals were distinctly detected with good reliability for RMS S/N ratios down to -16 dB. This lies very close to the detection margin expected for the steam generator protection system in a fast reactor.
- The analysis methods also detected leak signals even down to - 24 dB S/N, but with less reliability. Discrimination and reliability are enhanced even at such low S/N ratios by filtering techniques, if the leak signals contain specific frequency bands.
- The response time of detection was always less than 1 s.
- The cluster analysis and neural network technique are two methods available for improving the reliability of the detection system.
- The leak location was identified through the time domain with the beam forming technique using multi-channel analysis

4. Requirements for the KALIMER Acoustic Leak Detection System

The main requirements for the acoustic water - steam leak detection system in the KALIMER SG are for the sensitivity and response time of the system. The sensitivity of an acoustic system is perceived as the minimum leak rate of water-steam into sodium, which one can select in conditions of an industrial steam generator of the KALIMER system for minimum time from the moment the leak begins. The response time of an acoustic system in the KALIMER SG is perceived as the time from the moment the leak begins up to the moment of its detection.

Other main requirements for a water-steam leak detection system in the KALIMER SG are set up in [3] and are stated as follows: Intermediate leaks (10 - 1000 g/s) generally continue for about 30 seconds and the leak can be identified within 3 seconds by the acoustic detection system. From this definition it follows that the required sensitivity is 10 g/s, and the required response time is 3 seconds. For these requirements the experimental results are presented in Fig. 9.

These requirements follow from the necessity of avoiding a secondary leak owing to the destruction

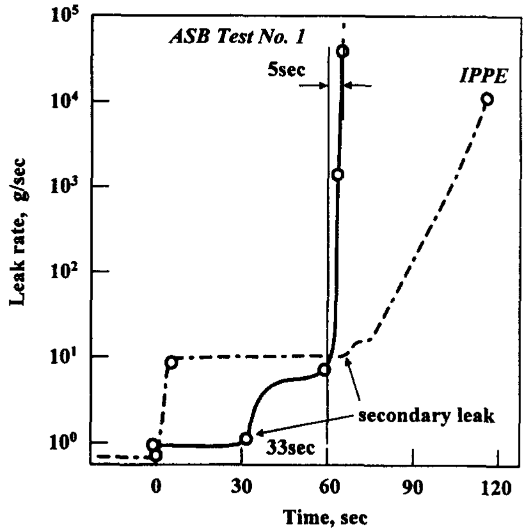

Fig. 9. Time Dependence of Water Leak Flow Rate

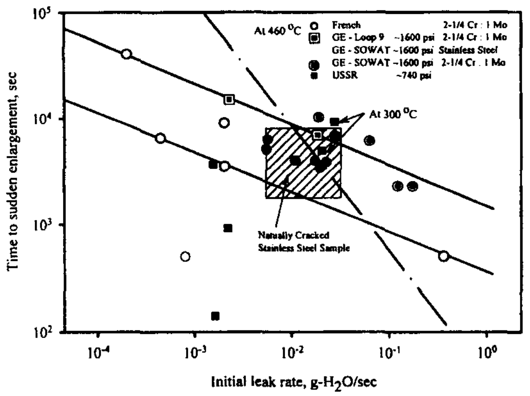

Fig. 10. Time to Sudden Enlargement vs. Initial Leak Rate(●; data of IPPE using KALIMER SG Structure Material, 2.25Cr 1Mo)

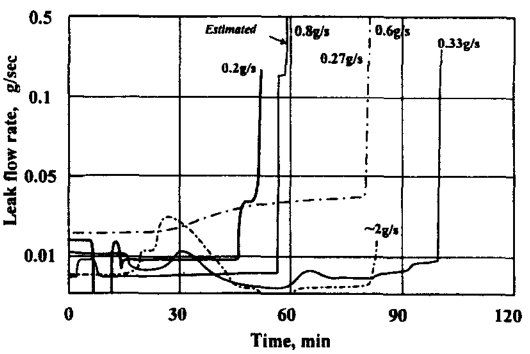

Fig. 11. Time Dependence of Water Leak Flow Rate(Estimated by Results of IPPE Experiments using KALIMER SG Structure Material, 2.25Cr 1Mo)

adjacent to a defective tube in the SG. This does not contradict modern submissions about the mechanisms and dynamics of defective tube self-development. The findings of an investigation [7] on leak self-development and wastage of tube - targets executed in IPPE using the structure material (2.25Cr 1Mo) of the KALIMER SG is shown in Fig. 10.

It is necessary to mark the relevance of these results, as they are unique results on micro leak self-development and allow detection before a sharp increase of the leak rate (initial leak rate from 0.005~0.01 g/s increases to 0.22~0.8 g/s) which could correspond to the destruction of a tube wall and which is generally 40~100 minutes from the beginning of a leak in Fig. 11.

Thus, for an acoustic leak detection system in the KALIMER SG the perspective requirements are the detection of an intermediate leak (10~1000 g/s) and also the detection of micro and small leaks. The detection of micro and small leaks will allow control of the leak development, to avoid a secondary leak and to avoid large destruction of a tube bundle in the KALIMER SG. On the whole the detection of micro and small leaks will allow increased safety for the KALIMER SG.

For the development of the KALIMER acoustic leak detection system it is necessary to execute the following stages of experimental activities: selection, complete set and test of acoustic measurements means in laboratory conditions; selection, complete set and test of a leak acoustic signal processing means; test of acoustic measurements means on a water model with gas injection in water for achievement of required sensitivity and required response time of leak detection; complete set and test of the prototype of an acoustic leak detection system in the KALIMER SG; test of the prototype KALDS in conditions of a sodium test facility for verification and confirmation of required sensitivity and required response time of leak detection; study of background noises in the KALIMER SG; test of the prototype KALDS in the conditions of the KALIMER SG with a hydrogen detection system during the injection experiment of water - steam into sodium.

5. Conclusions

Up to the present time in the USA, UK, France, Germany, Japan and Russia positive experience with passive acoustic leak detection method development has been accumulated.

Much experimental research on leak noise in the conditions of sodium test facilities firstly for the detection of an intermediate leak (10~1000 g/s), and also for the detection of small and micro leaks (0.01 g/s and more than 0.01 g/s) for a sodium temperature of 300℃ ~500℃, has been completed.

The acoustic measurements of background noises of industrial steam generators SPhx1, PFR, and BN-600 in different modes of power have been established. Within the framework of the IAEA research coordinated program, different methods of allocation and separation of leak noise (leak data of the IPPE, and the ASB) from background noise in the SG (background noise data of the PFR SG, and the SPhx1) have been designed, which are reliable in selecting the noise of a small leak at a ratio of S/N = -20 dB in no more than 1 second.

Existing experience can be successfully applied for the development of an acoustic leak detection system for the detection of water-steam leaks into sodium in the KALIMER SG.

There was designed, made and stored in the KAERI experimental test facilities (water model for acoustic research on noise at the gas jet out-flow in water, water model of the KALIMER SG) with acoustic emission (AE) sensors with a pre-amplifier system to be able to extend for long distance, Pegasus as the DSP (digital signal processing) software in real-time (Jovian Systems, Inc.) combined with NeuroSolution software (NeuroDimension, Inc.) for solving the Neural Network approach which allows the development of an acoustic leak detection system which fulfills the conditions of the KALIMER project.

For the development of an acoustic leak detection system in the KALIMER SG completion of the following experimental research is necessary: the testing of acoustic sensors and hardware to confirm its availability for leak detection conditions; acoustic noise measurements when Argon gas is injected into water using a mock-up model; acoustic noise measurements when Argon gas is injected into water inside a helical coil using the water model as the KALIMER SG; injection noise of Argon gas and water-steam into sodium using a sodium test facility; study of the steam generator' s background noise; and development of the prototype of an acoustic leak detection system for the KALIMER SG.

Acknowledgment

This study was performed under the auspices of the Korea Ministry of Science and Technology (MOST). The authors wish to gratefully thank the MOST for their support.

Nomenclature and Abbreviation

a_h	Temperature conductivity of hydrogen bubble
$c_{1,2,3}$	Sound velocity of water, steel, and sodium
C_{Na}	Sound velocity in sodium
c_s	Sound velocity of steam
c_w	Sound velocity of water
f	Frequency of oscillation
f_o	Frequency of hydrogen bubble oscillation
n	$= 2\pi/\lambda$
P	Steam pressure
P_o	Pressure of hydrogen in bubble
p_{Na}	Static pressure in sodium
R_o	Radius of hydrogen bubble
BN	Bystry Neutron (Fast Neutron)
IPPE	Institute of Physics and Power Engineering
KALDS	KALIMER Acoustic Leak Detection System
KALIMER	Korea Advanced LIquid MEtal Reactor
NPP	Nuclear Power Plant
PFR	Prototype Fast Reactor
SG	Steam Generator

Greek Letters

α	Ratio of steam by volume
δ	Attenuation coefficient
δ_T	Thermal attenuation
δ_R	Radiation attenuation
δ_V	Viscosity attenuation
γ	C_p/C_v
η	$= 2\pi R_o/\lambda$
λ	Length of sound wave
μ_{Na}	Dynamic viscosity coefficient of sodium
$\rho_{1,2,3}$	Density of water, steel, and sodium
ρ_m	Density of water-steam mixture
ρ_{Na}	Density of sodium
σ	Surface tension force

References

1. IAEA-TECDOC-1083, "Status of liquid metal cooled fast reactor technology", April (1999).
2. KAERI/TR-888/97, KALIMER Design Concept Report, July (1997).
3. KALIMER/FS400-DD-01-Rev.1/1999, "System Description for Steam Generation System", KAERI, Taejon, Korea (1999).
4. F.A. Kozlov, "Studies on Some Problems of Leaks in Sodium-Water Steam Generators", Proc. Internat. Conf. On Liquid Metal Technology in Energy Production, USA (1976).
5. D.A. Greene, G. W. Malovrh, P. M. Magee, and D. R. Dixon, "Acoustic Leak Detection Development in the USA", Liquid Metal technol. BNES, 1, (1984).
6. IAEA-TECDOC-866, "Sodium-Water Interactions in Steam Generators", (1996).
7. Annual Report on the Agreement 410/0862430/30-12-98 Between KAERI and IPPE, "Development of ALDS, Investigation of Water-in-sodium Leak Self Development", May (1999).
8. AIX-EN-PROVANCE, FRANCE. 1-3 October 1990 IAEA IWGFR/79, "Proceedings of the Specialists' Meeting on Acoustic/ultrasonic Detection of in Sodium Water Leaks on Steam Generators", (1990).
9. IAEA-TECDOC-946, " Acoustic Signal Processing for the Detection of Sodium Boiling or Sodium-water Reaction in LMFRs", May (1997).
10. C. Devin, "Survey of Thermal, Radiation and Viscouse Damping of Pulsating Air Bubbles in Water", Journal of the Acoustic Society of America, Vol. 31, No. 12, December (1959).
11. Byeung-Tae Min, Yoon-Sub Sim, and et.al., " KALIMER Steam Generator Design Characteristics", Proceedings of the Korean Nuclear Society Autumn Meeting, Seoul,

Korea, October (1998).

12. Leighton, "The Acoustic Bubble", Academic press, 295 (1994).
13. L. Camp, "Under water acoustics", Moscow, MIR, (1972).
14. L. G. Loutshjansky, "Mechanics of liquid and gas", Moscow, Nauka, (1970).
15. V. S. Yughay and F. A. Kozlov, "Water into sodium leak noise spectra", Atomnija Energija, 65, 17-20 (1988).
16. V. M. Poplavsky and F. A. Kozlov, "Sodium-Water Steam Generator Safety" Eneryoatomizdat, Moscow, 48 (1990).