Sodium Combustion Analysis Code: ECHOES and Its Application to Sodium Burning in an LMFBR Secondary System

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A computer code ECHOES has been prepared at the Institute of Nuclear Safety to analyze thermo-hydraulics of sodium combustion event in the secondary system of LMFBR, by combining a spray fire code SPRAY-III and a pool fire code SOFIRE-II and by adding analytical capabilities to calculate the key elements of the phenomena, such as the expansion of the sodium pool, the release of water from the heated concrete wall and the corrosion of the steel floor-liner. The present code models the atmosphere of the room where sodium leakage occurred with one point, and structures one- or two-dimensionally. One-though analysis is possible with this code on the effect of sodium leakage on the structure of the reactor plant. Calculations were performed for several experiments to validate the code. It was shown that the code gives reasonable results to the temperatures of atmosphere, sodium pool, floor-liner, wall and the atmosphere oxygen concentration. Trial calculations were performed by applying ECHOES to the sodium leakage in the secondary system of Monju. The leak rate was changed from 0.01 t/h to 134 t/h. Followings were revealed from these calculations. (1) The steel floor-liner decreased about 3 mm in the thickness at the maximum to the initial thickness of 6 mm, although such severe corrosion condition is hard to occur in LMFBR plant. (2) The maximum atmospheric hydrogen concentration was 0.7 %, that is well small compared to the burning limit (4%).

KEYWORDS: LMFBR, Safety analysis, Sodium burning, Computer code, Floor liner

I. Introduction

One of main features of safety evaluation of LMFBR (Liquid Metal cooled Fast Breeder Reactor) is consideration of chemical reactions of sodium. Because usually rooms in the LMFBR secondary cooling system is filled by air, the spilled sodium from a defect of the coolant boundary will catch fire soon. One of main objectives in past researches on sodium leak accident is the evaluation of the generated pressure pulse by a large-scale sodium spray. On the other hand, the locally formed sodium pool on the floor due to the small-scale sodium leakage has not been so much noticed because the sodium will be kept on the steel-liner or drain through a drainpipe to a reservoir installation. However, the small-scale leakage should be also evaluated enough from not only its higher probability but also from the thermal and chemical effect to the soundness of the steel-liner by the sodium pool that contains sodium oxides.

In the present work we intended to analyze the sodium fire phenomena more realistically from the beginning to the end for a wide range of leak rate. Two types of sodium burning code, one is to deal with the spray fire and the other to the pool fire, had been developed separately so far. In developing our computer code the first step was to make it possible to analyze the combined fire where spray and pool fires are taking place simultaneously. It has been done by combining a sodium spray fire code SPRAY-III and a sodium pool fire code SOFIRE-II. Then, several functions, such as (1) expansion and flow of sodium pool, (2) water release (vaporization) from the heated concrete wall, and (3) evaluation of the wasted thickness of the steel-liner, were added. This paper describes the models involved in the combined code, named ECHOES for convenience, and the results of validation calculations to experimental data. Some application calculations to an LMFBR plant condition are also shown.

II. Analytical model

1. Chemical reactions and atmospheric gas transfer

Two chemical formulas are included for sodium burning in the ECHOES code.

[A] \[2 \text{Na} + \frac{1}{2} \text{O}_2 \rightarrow \text{Na}_2\text{O}\] (1)

[B] \[2 \text{Na} + \text{O}_2 \rightarrow \text{Na}_2\text{O}_2\] (2)

The reaction [B] is considered to take place when the oxygen concentration is high, such as over 10 %. Reactions between sodium and water, and between sodium oxides and water are considered to occur by following equations.

\[2 \text{Na} + \text{H}_2\text{O} \rightarrow \text{Na}_2\text{O} + \text{H}_2\] (3)

\[\text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O}\] (4)

\[\text{Na}_2\text{O} + \text{H}_2\text{O} \rightarrow 2 \text{NaOH}\] (5)

\[\text{Na}_2\text{O}_2 + \text{H}_2\text{O} \rightarrow 2 \text{NaOH} + \frac{1}{2} \text{O}_2\] (6)

\[\text{Na}_2\text{O} + 3 \text{H}_2\text{O} \rightarrow 2 \text{NaOH} + \text{H}_2\text{O}\] (7)

\[\text{Na}_2\text{O}_2 + 3 \text{H}_2\text{O} \rightarrow 2 \text{NaOH} + \text{H}_2\text{O} + \frac{1}{2} \text{O}_2\] (8)

The atmospheric gas flow to outside is possible not only by the forced gas supply by air conditioner but also by the...
pressure difference between both sides.

2. Model of local sodium pool expansion

In the case of small leak, a local sodium pool is formed. Even in the case of large leak, a pool expansion process appears till the pool covers all over the floor. To deal with such sodium pool expansion we added a model considering circular pool formation. As is shown in Fig.1, the pool is divided into several rings of a same area (including the central circle). At first the pool is formed where sodium droplets fall. Then, the sodium flows from the inner ring to the outer according to the height difference. Eq. (9) represents the sodium flow.

\[
\frac{\Delta m_i}{\Delta t} = w_{i,i+1}^f - w_{i,i+1}^i + w_{i,i+1}^i \times (1 - \eta) + C \times \rho(T_{i+1}) \times S_{\text{vol},i} \times \sqrt{2g\Delta h_{i,i+1}} - C \times \rho(T_i) \times S_{\text{vol},i} \times \sqrt{2g\Delta h_{i,i+1}}
\]

(9)

Where,
- \(C\): coefficient for sodium transfer (-)
- \(g\): acceleration of gravity (m/s²)
- \(m_i\): mass of sodium and sodium-oxides mixture in Ring \(i\) (kg)
- \(S_{\text{vol},i}\): vertical area between Ring \(i\) and Ring \(i+1\) (m²)
- \(w_{i,i+1}^f\): production rate of reaction products in Ring \(i\) (kg/s)
- \(w_{i,i+1}^i\): falling rate of sodium droplets in Ring \(i\) (kg/s)
- \(w_{i,i+1}^c\): consumed rate of sodium in Ring \(i\) (kg/s)
- \(\Delta h_{i,i+1}\): height difference between Ring \(i\) and Ring \(i+1\) (m)
- \(\eta\): ratio of reaction products produced in forms of aerosol (-)
- \(\rho(T_i)\): density of sodium and sodium-oxides mixture corresponding to the temperature of Ring \(i\) (kg/m³).

If the height of the outmost sodium exceeds a limit value \(h_{\text{max}}^c\), it is assumed that the sodium pool expands to the neighboring dry ring.

The coefficient for sodium transfer was obtained from a shape of remained after burning in an experiment.

3. Flow model of sodium pool

When the sodium leak rate is so large that the spilled sodium flows out to touch the side wall, it is assumed that the pool changes its shape keeping the area from circular to rectangular. The width of the rectangular pool is identical with that of the room. Then the pool expands toward the drainpipe (Fig.2). The pool expansion speed, \(v\) (m/s) is obtained by eq. (10) using Manning’s equation to an open-channel flow.

\[v = \frac{1}{n} \left( \frac{h}{n} \right) \frac{1}{3} \sqrt{\sin \theta}
\]

(10)

Where,
- \(n\): roughness factor of floor (s/m³/²)
- \(\theta\): incline of floor (degree)

Discharge of sodium from the floor begins when the pool front reaches the drainpipe. The drain flow rate \(Q_{\text{drain}}\) is expressed by eq. (11).

\[Q_{\text{drain}} = v \times h \times L_d
\]

(11)

Where,
- \(L_d\): inner circumferential length of the drainpipe (m)

4. Model of water release from concrete wall

At relatively low temperature less than some hundred-degree C, the absorbed water in concrete is released leaving water contained in the crystal. It is revealed from the Sodium Leak and Fire Test-II performed by PNC (Power Reactor and Nuclear Fuel Development Corporation) that the water released from concrete plays an important role to form NaOH, that allows Na₂O₂ to contact
with the floor-liner when the NaOH concentration reached a dense condition in the sodium pool.

Followings were assumed on the water release from the concrete wall.
(1) When the concrete temperature is less than 60 degree C, all heat added to the node is used to heat up the concrete.
(2) When the concrete temperature $T_{con}$ is more than 60 degree C and less than 100 degree C, the ratio of the heat used to evaporate the absorbed water $\lambda$ is given by

$$\lambda = a \times \exp\left(-\frac{b}{T_{con}}\right)$$

(12)

Where, $a$ and $b$ are given through fitting the experimental data.
(3) Once the concrete temperature reaches 100 degree C, all heat added is used to evaporate the absorbed water.
(4) A time lag is considered when the water released in an inside-layer of the concrete wall to move to the adjacent layer that is nearer to the concrete surface.

In an experiment performed by PNC, the concrete surface was heated and the temperature change inside the concrete were measured (Fig.3). The calculated temperatures derived from ECHOES were compared with measured resulting in a good agreement between them. Figure 4 shows that the time history of the accumulated water mass from the concrete compares well with that calculated.

5. Corrosion model of steel liner by reaction products
The corrosion rate of steel liner attacked by sodium oxides is expressed by eq.(13).

$$\frac{dL}{dt} = C' \exp\left(-\frac{C''}{T}\right)$$

(13)

Where,
$C'$, $C''$: constant (-)
$L$: liner thickness (mm)
$T$: liner temperature (K)

The values of $C'$ and $C''$ change drastically with the NaOH concentration in the sodium pool. When the concentration of NaOH which has no deoxidation effect exceeds a certain value, the change of the corrosion mechanism occurs. In a molten salt reaction (a kind of chemical reactions) where the remained $Na_2O_2$ controls the corrosion, the floor-liner is mostly severely corroded. The values $C'$ and $C''$ are settled from JNC (Japan Nuclear Cycle Development Institute, the reincarnation of PNC)’s experimental date of steel specimens in the molten salt.

III. Verification with experimental data
Several experimental data were used to verify the code. Some of them are introduced here.

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Fig.2  Model of sodium pool formation and experiment

Fig.3  Time history of concrete temperature
1. Sodium pool expansion test (F7-1)

A series of sodium release test were performed by JNC to measure the floor temperature and to observe the sodium pool expansion in a small leak rate condition (about 0.01 t/h). The results of F7-1 were compared with the calculated ones.

The experimental conditions were,
- Container volume: 0.434 m³
- Released sodium temperature: 505 degree C
- Release time: 1,505 s
- Height of release nozzle from floor: 0.1 m
- Sodium leak rate: 3.3 g/s
- Air exchange rate: 3 m³/min

The dimensions of the spray in the calculation is
- Top radius of the spray cone: 0.01 m
- Expansion of the spray cone: 20 degree

Figure 5 shows how the process of the pool expansion. It was judged from the floor temperature data and the trace of the pool edge was compared with that calculated. In the calculation it was assumed that the sodium pool flows outwards when the outermost pool level exceeded 5 mm. The measured and calculated liner temperatures beneath the release nozzle are shown in Fig. 6. These figures indicate that the agreement between experiment and calculation is good.

2. Sodium pool test (TASP-A2)

A relatively large leak rate test named TASP-A2 was performed by PNC mainly to measure the gas pressure change shortly after the release inception.

The experimental conditions were,
- Container volume: 21 m³
- Released sodium temperature: 512 degree C
- Release time: 57 s
- Height of release nozzle from floor: 3 m
- Sodium leak rate: 172 g/s
- Air exchange rate: 0 m³/min

The dimensions of the spray in the calculation is
- Top radius of the spray cone: 0.01 m
- Expansion of the spray cone: 20 degree

Figure 7 shows the measured and calculated liner temperatures. Whereas the thermocouples were set at different locations from the center and the spray droplet directly fell on the central four points, the calculated represents the pool mean temperature. The calculated pressure in the room (Fig. 8) is higher than that measured. These figures indicate that the calculated pool temperature agreed well with measured after a transient for some tens seconds. The higher calculated pressure than the measured shows a bit of conservatism in the safety analysis of LMFBR plant.
3. Sodium Leak and Fire Test - II

In the Sodium Leak and Fire Test - II (Test-II) performed by PNC, they intended to simulate conditions of the Monju sodium leak incident in 1995 as far as possible. However, they could not simulate the vast room of Monju. The container volume of experiment was one order smaller. The experimental conditions were,

- Container volume: 170 m$^3$
- Floor area: 23.6 m$^2$
- Released sodium temperature: 480 degree C
- Release time: 13320 s
- Height of release nozzle from floor: 3.6 m
- Sodium leak rate:
  - 54 g/s (from 0 s to 10,620 s),
  - 48 g/s (from 10,620 s to 11,400 s),
  - 39 g/s (from 11,400 s to 13,320 s)
- Air exchange rate: 33 m$^3$/min
- Height of spray: 3.6 m
- The dimensions of the spray in the calculation is
- Top radius of the spray cone: 0.01 m
- Expansion of the spray cone (one side): 20 degree

Figure 9 shows the measured and calculated pool temperatures. Whereas the thermocouples were set at different location from the center and the spray droplet directly fell over the two thermocouples, the calculated represents the pool mean temperature, which agreed well with the measured at the central region of the floor particularly at the beginning two hours. The average concrete wall temperature measured is well simulated by the calculation as shown in Fig.10. The calculated and measured temperature exceeded 100 degree C. It means that the water is released in a large scale. After then the large mount of produced NaOH caused Na$_2$O$_2$ to attack the floor-liner severely.

Two gas temperatures are calculated by ECHOES (Fig. 11). The higher one corresponds to inside of the spray cone and it is less than the measured by about 50 degree C. If we understand that the burning droplets often touched the thermocouples, it is reasonable the calculated is less than the measured. The agreement of the room atmosphere temperature is quite well. During this experiment the oxygen concentration did not make a marked change, because the air exchange system was operated as was the case of the accident (Fig. 12).

As shown above it was revealed that the ECHOES code made good performances in the validation calculations.

VI. Calculation to LMFBR Condition

Sample calculations were performed to check the applicability of ECHOES to Monju. The largest room of the secondary system was chosen and followings are the main inputs for the calculation.

Fig. 7  Time history of pool temperature: TASP-A2 Test

Fig. 8  Time history of gas pressure: TASP-A2 Test
Room volume: 3,300 m$^3$
Floor area: 560 m$^2$
Floor-liner: 6mm-thick steel, incline of 1/100
Wall and ceiling: 2 m-thick concrete covered by 15 mm-thick insulator.
Released sodium temperature: 507 degree C
Release rate: 0.01 t/h - 134 t/h
Release time: 1,800 s – 2,400 s
Quitting time of the air conditioner: 120 s
Air exchange rate: 1,700 m$^3$/h (ΔP $\leq$ 50 mmAq)
17,100 m$^3$/h (50 mmAq < ΔP $\leq$ 500 mmAq)
39,900 m$^3$/h (500 mmAq < ΔP )
*Values at ΔP = 100 mmAq
** ΔP : pressure difference between inside and outside of the room

Figure 13 shows the effect of the leak rate on the peak temperature of the floor-liner. The liner peak temperature takes the maximum value at a leak rate of 0.7 t/h. The peak temperature once decreases in the leak rate range more than 1t/h and again it increases when the leak rate expands 10 t/h. This peak temperature change is explained as follows. While the leaked sodium forms a local pool, the liner temperature increases with the leak rate. The sodium pool begins to expand all over the floor in the leak rate range more than 3 t/h. The liner that was newly covered by the pool works as a heat sink and cools the expanding sodium pool. However, the heat of the falling sodium begins to prevail the heat sink effect as the leak rate increases. Figure 14 shows the lost liner thickness during the leakage. Because in the corrosion processes the liner temperature plays a superior effect, the marked thickness lose occurs only when the temperature exceeds 600 degree C. It must be mentioned that this evaluation was made assuming that the molten salt reaction of Na$_2$O$_2$ and that such situation does not occur in a dry atmosphere. Even at the unrealistically severe condition, the thickness loses was less than the half of the original. On the other hand, the increase of hydrogen concentration is so small (0.7 %) as shown in Fig.15 that it does not reach the burning limit of 4 %.

Same calculations were also performed to other rooms and we got the similar results.

V. Conclusion
A computer code, which covers from small-scale to large-scale sodium leakage considering the movement of the sodium pool, was prepared to analyze the sodium leak phenomena in the secondary system of LMFBR. This work began with combining a spray fire code SPRAY-III with a pool fire code SOPFIRE-II for realistic analysis. The validation calculation of the ECHOES code showed good agreements with the experimental data. Calculations to the Monju condition was performed and the effects of the leak
rate to the floor-liner temperature, floor-liner corrosion and hydrogen production were shown. Followings were revealed from these calculations. (1) The steel floor-liner decreased about 3 mm in the thickness at the maximum to the initial thickness of 6 mm. (2) The maximum atmospheric hydrogen concentration was 0.7 %, which is well small compared to the burning limit (4%).

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References