KAERI/TR-2002/2002

소듐 누출로 인한 소듐 연소 현상 분석

Analytical study of sodium combustion phenomena under sodium leak accidents

2002. 1

한국원자력연구소

제출문

한국원자력연구소장 귀하

본 보고서를 "소듐 누출로 인한 소듐 연소 현상 분석"에 대한 기술보고서로 제출합니다.

2002년 1월

주저자: 김병호
공저자: 정지영
정경채
김태준
최종현

요약문

고속증식로의 화전안전대책을 마련하기 위하여 소듐화재로 인한 에어로졸의 방출, 빌딩내에서의 온도 및 압력의 상승을 고려하는 것이 중요하다. 이러한 이유 때문에 다양한 소듐누출에 기인한 소듐화재의 특성을 파악할 필요가 있다. ASSCOPS(Analysis of Simultaneous Sodium Combustion in Pool and Spray)는 고속증식로에서 소듐 누출 및 화재사고를 분석하기 위하여 Japan Nuclear Cycle Development Institute(JNC)에 의하여 개발된 코드이다. 본 연구에서는 ASSCOPS code를 사용하여 KALIMER(Korea Advanced Liquid Metal Reactor)의 증기발생기에서의 소듐 누출 및 화재사고에 대한 예비분석을 수행하였다. 분무형 및 풀형 소듐 연소현상, 건물내에서의 압력 및 온도변화, 구조재의 온도변화, 에어로졸 거동, 안전밸브를 갖춘 건물에서의 환기 특성, 불활성기체의 유입에 따른 화재영향 등이 평가되었다. 계산결과, 소듐화재 발생후 소듐누출이 파이프 시스템으로부터 얼마나 지속되는가에 따라서, 환기시스템의 가동 여부, 불활성 기체의 유입 여부 및 시점, 누출된 소듐의 drain 여부, 그리고 건물의 외부로부터의 격리 여부에 따라서 차후 화재영향이 다양하게 나타났다. 특히, 각 건물의 벽면에 압력개방판을 설치함으로써 과도한 압력 상승을 미연에 방지 할 수 있었다.

Abstract

The rise of temperature and pressure, the release of aerosol in the buildings as a result of sodium fire must be considered for the safety measures of LMR. Therefore for the safety of the LMR, it is necessary to understand the characteristics of sodium fire, resulting from the various type of leakage. ASSCOPS(Analysis of Simultaneous Sodium Combustion in Pool and Spray) is the computer code for the analysis of the thermal consequence of sodium leak and fire in LMR that has been developed by Japan Nuclear Cycle Development Institute(JNC) in Japan. In this study, a preliminary analysis of sodium leak and fire accidents in S/G building of KALIMER is made by using ASSCOPS code. Various phenomena of interest are spray and pool burning, peak pressure, temperature change, local structure temperature, aerosol behavior, drain system into smothering tank, ventilation characteristics at each cell with the safety venting system and nitrogen injection system.

In this calculation, the dimension of the S/G building was chosen in accordance with the selected options of LMR name KALIMER(Korea).

As a result of this study, it was shown that subsequent effect of sodium fire depended upon whether the sodium continued to leak from the pipe or not, whether the ventilation system was running, whether the inert gas injection system was provided, whether the sodium on floor was drained into the smothering tank or not, whether the building was sealed or not, etc. Specially the excessive rise of pressure into each cell was prevented by installing the pressure release plates on wall of the building.

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1. Introduction

The use of sodium as a coolant in liquid metal reactor(LMR) has many advantages due to its thermal properties while a disadvantage that a major sodium spill and a pipe rupture of sodium coolant systems will usually result in sodium fire. The rise of temperature and pressure, the release of aerosol in the buildings as a result of sodium fire must be considered for the safety measures of LMR. Subsequent effect of sodium fire depends upon whether the sodium continues to leak from the pipe or not, whether the ventilation system is running, whether the inert gas injection system is provided, whether the sodium on floor is drained into the smothering tank or not, whether the building is sealed or not, etc. Therefore for the safety of the LMR, it is necessary to understand the characteristics of sodium fire, resulting from the various type of leakage.

ASSCOPS(Analysis of Simultaneous Sodium Combustion in Pool and Spray) is the computer code for the analysis of the thermal consequences of sodium leak and fire in LMFR that has been developed by Japan Nuclear Cycle Development Institute(JNC) in Japan. ASSCOPS computer code includes two sodium combustion codes called SOFIRE II and SPRAY. SOFIRE II code has been developed to compute 1-cell and 2-cell pool fire cases by Atomics International(AI), and SPRAY code has been developed to evaluate the consequences of a postulated sodium spray release from LMFR piping leak by Hanford Engineering Development Laboratory(HEDL) in USA.

ASSCOPS performs constantly the calculation of thermodynamics, heat transfer, mass transfer and combustion of sodium pool and spray droplets for a range of oxygen and water vapor concentration, leak rate and temperature of sodium, cell geometry such as cell volume, the surface area and the thickness of structures, etc.

ASSCOPS is able to evaluate sodium fire phenomena in the reactor building consisting of two cells. Namely, it is possible for ASSCOPS to analyze sodium pool combustion in 1-cell, both the sodium pool combustion and the spray combustion, either sodium pool combustion or spray combustion in 2-cell. Also, ASSOCOPS has options to exhaust and ventilate the cells at a given rate, to simulate the gas leak between cells and atmosphere, and the gas flow between 1-cell and 2-cell by natural convective heat transfer and pressure difference of cells.

Meanwhile, The LMR Design Technology Development Project was approved as a national long-term R&D program in 1992 by the Korea Atomic Energy Commission (KAEC), which decided to develop and construct an LMR. Based upon the KAEC decision, the Korea Atomic Energy Research Institute (KAERI) has been developing LMR named KALIMER(Korea Advanced LIquid Metal Reactor). According to the revised National Nuclear Energy Promotion Plan of June, 1997, the basic design of KALIMER will be completed by 2006 and the possibility of construction will be considered sometime during the mid 2010s.

This report describes ASSCOPS code features, a preliminary analysis of sodium leak and fire accidents in S/G building of KALIMER, which is made by using ASSCOPS code. Various phenomena of interest are spray and pool burning, peak pressure, temperature change, the drain system into smothering tank, ventilation characteristics at each cell with the safety venting system and nitrogen injection system.

2. ASSCOPS computational model

2.1 Summary

Fig. 1 shows the performance of ASSCOPS. ASSCOPS can deal with other phenomena including sodium combustion in two cells called 1-cell and 2-cell, respectively. It is possible for ASSCOPS to treat simultaneously both the spray fire resulting from the break of pipe and pool fire. Also pool fire phenomena can be evaluated in 1-cell. Pool combustion by SOFIRE module in 1-cell, pool and spray combustion by spray in 2-cell are calculated. Pool condition(sodium temperature, sodium amount, pool surface area), gas atmosphere condition(gas temperature, gas composition etc.), and structure condition are specified in the input of SOFIRE module to calculate heat/mass transfer resulting from pool combustion. Meanwhile, Spray condition(sodium temperature, sodium leak rate, droplet diameter etc.), gas atmosphere condition(gas temperature, gas composition etc.), and structure condition(property, temperature, surface area etc) are specified in the input of spray module to calculate heat/mass transfer resulting from pool and spray combustion. Also, ASSOCOPS considers the transfer of sodium and sodium hydroxide from pool in 2-cell move to pool in 1-cell. And ASSOCOPS involves the gas flow between cells and transfer of aerosol(Sodium monoxide, sodium peroxide, sodium hydoxide).

The main features of ASSCOPS describe;

- Sodium pool combustion and spray combustion(reaction with water vapor including generation and heat evolution of hydrogen)
- Heat transfer and temperature change in the each compartment resulting from sodium combustion
- The evolution of water vapor from the concrete of structure to the cell atmosphere
- Gas pressure change in the cell
- Gas flow from cell to cell and from cell to atmosphere
- Aerosol behavior generated by sodium combustion(float, sedimentation and transfer between cells etc.)
- Reaction of aerosol(sodium oxide) with water vapor

ASSCOPS deals with such several phenomena as;

- 1-cell: pool combustion, heat/mass transfer accompanied by sodium combustion, aerosol behavior resulting from sodium combustion, evolution of water vapor from concrete structure to atmosphere in cell, reaction of sodium(pool) with water vapor, reaction of oxide(aerosol and pool) with water vapor, reaction of oxygen with

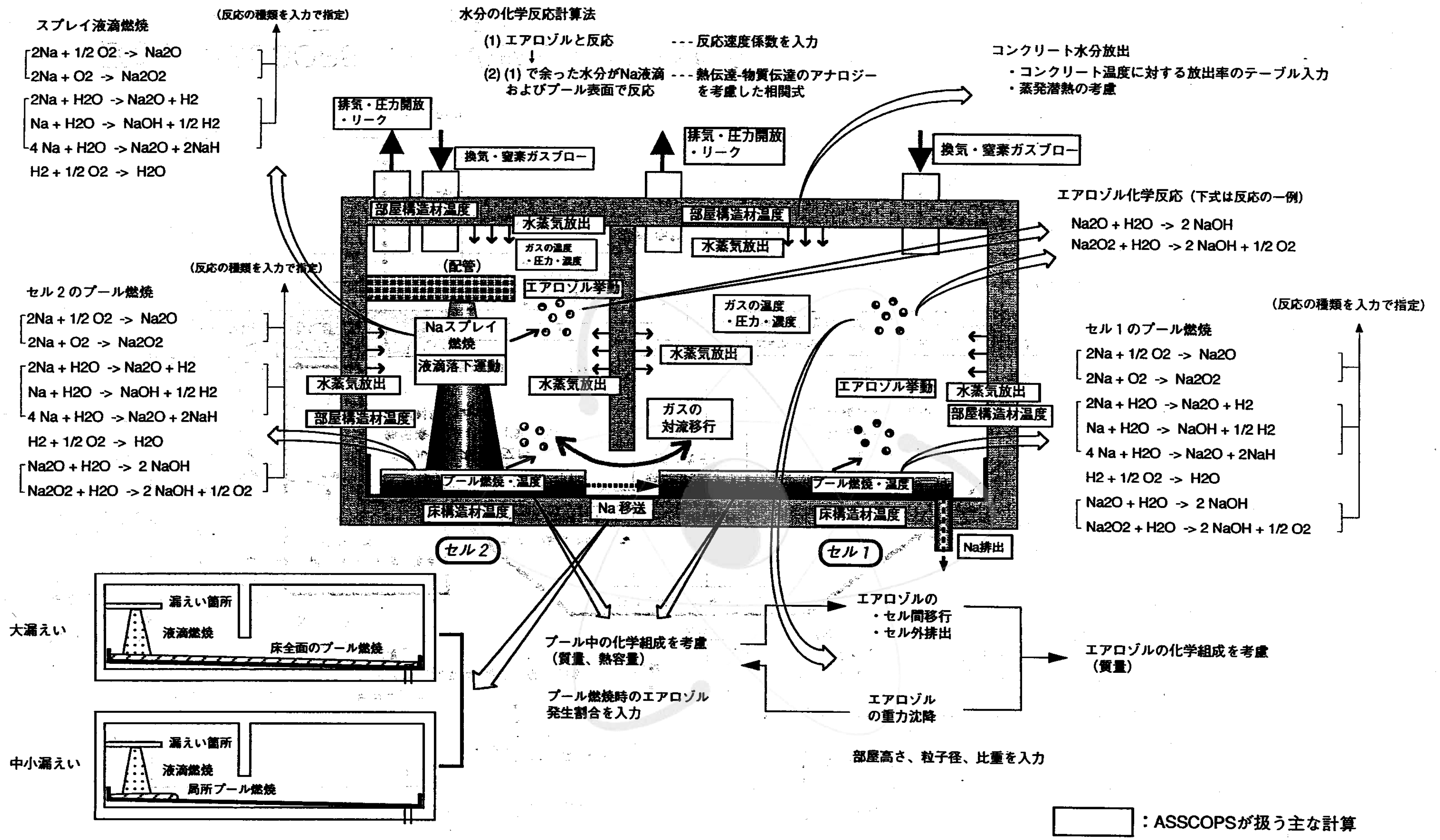


Fig. 1. The performance of ASSCOPS.

hydrogen generated by the reaction of water vapor-sodium

- 2-cell: Spray combustion, heat/mass transfer accompanied by sodium combustion, aerosol behavior resulting from sodium combustion, evolution of water vapor from concrete structure to atmosphere in cell, reaction of sodium(spray and pool) with water vapor, reaction of oxide(aerosol and pool) with water vapor, reaction of oxygen with hydrogen generated by the reaction of water vapor-sodium
- 3-Cell: Gas flow and leak behavior between 1-cell and 2-cell

Fig. 2 shows the network model for the heat/mass transfer which can be obtained by ASSCOPS.

2.2 SOFIRE model

SOFIRE is the code which computes a pool combustion and chemical reaction, heat generated by chemical reaction, pool temperature in 1-cell, and gas temperature and pressure transient of each structure, evolution of water vapor from the concrete of structure and aerosol behavior in 1-cell and 2-cell, The followings describe SOFIRE model.

2.2.1 Chemical reaction

When the sodium burns, two reactions occur.

$2Na(l)+1/2O_2(g) \rightarrow Na_2O(s)$ △h= -435kJ/mol-Na_2O (1)

$2Na(l)+O_2(g) \rightarrow Na_2O_2(s)$ △h= -519kJ/mol-Na_2O_2 (2)

The fraction of monoxide(1) and peroxide(2), which are dependent on the oxygen concentration, is determined by choice of input data.
Three reactions of sodium with water vapor considered on the pool are:

$2Na(l)+H_2O(g) \rightarrow Na_2O(s)+H_2(g)$ △h= -173kJ/mol-Na_2O (3)

$Na(l)+H_2O(g) \rightarrow NaOH(s,l)+1/2H_2(g)$ △h= -435kJ/mol-NaOH (4)

$4Na(l +H_2O(g) \rightarrow Na_2O(s)+2NaH(s,l)$ △h= -313kJ/mol-Na_2O (5)

The fraction of the above equation (3), (4) and (5) is specified in input.
Aerosol is released in proportion to the ratio of Na_2O, Na_2O_2, and NaOH generated by eq.(1), (2), (3), (4) and (5), which is specified in input. Also, sodium oxide(sodium oxide, sodium peroxide) remaining on the pool as aerosol reacts to water vapor, but sodium peroxide as reactants remains on the pool.

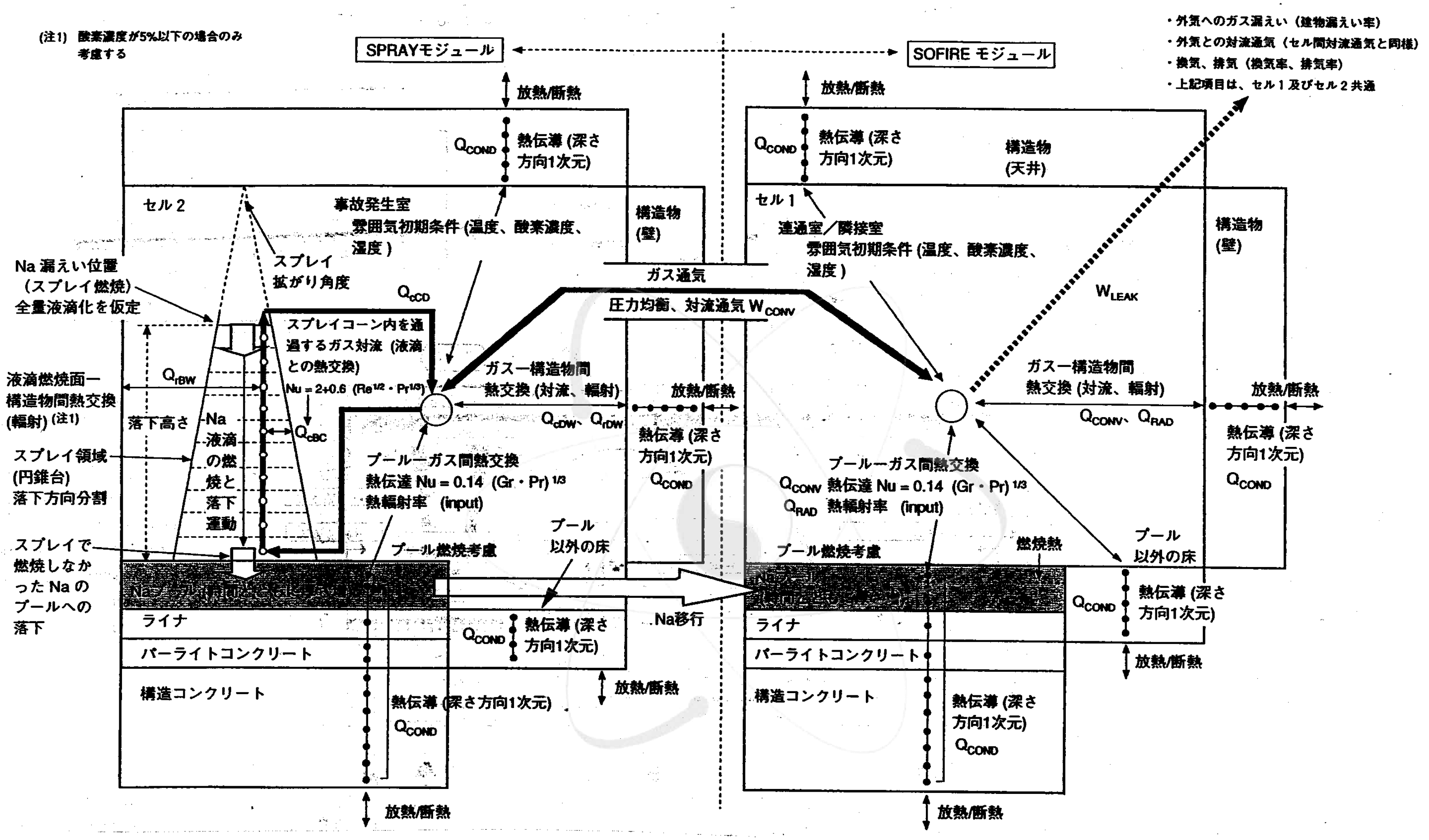


Fig. 2. The network model for the heat/mass transfer which can be obtained by ASSCOPS.

There are two kinds of reactions as follows.

$Na_2O(s)+H_2O(g)\rightarrow 2NaOH(s,l)$ $\quad \triangle h= -98kJ/mol\text{-}NaOH$ (6)

$Na_2O_2(s)+H_2O(g)\rightarrow 2NaOH(s,l)+1/2O_2(g)$ $\triangle h= -50kJ/mol\text{-}NaOH$ (7)

Aerosol(sodium oxide, sodium peroxide) floating in the gas atmosphere is treated as the total amount of those resulting from pool combustion as described above and spray combustion(section 2.3.1), respectively. In this limit, sodium oxide is assumed to react to water vapor and the reaction ratio is specified in the input. Reaction of sodium oxide in aerosol with water vapor is expressed by the above eq.(6) and (7). For this purpose, aerosol is treated as sodium monoxide, sodium peroxide, sodium hydoxide as described in the following section(2.2.9).

Also, in case that hydrogen generated by eq.(4)and(5) is present as much as oxygen in gas atmosphere and sodium continues to burn, hydrogen reacts to oxygen as eq.(8).

$H_2(g)+1/2O_2(g)\rightarrow H_2O(g)$ $\quad \triangle h= -242kJ/mol\text{-}H_2O$ (8)

The proportion of hydrogen and the lower values of oxygen concentration required for the reaction of eq.(8) is specified in the input.

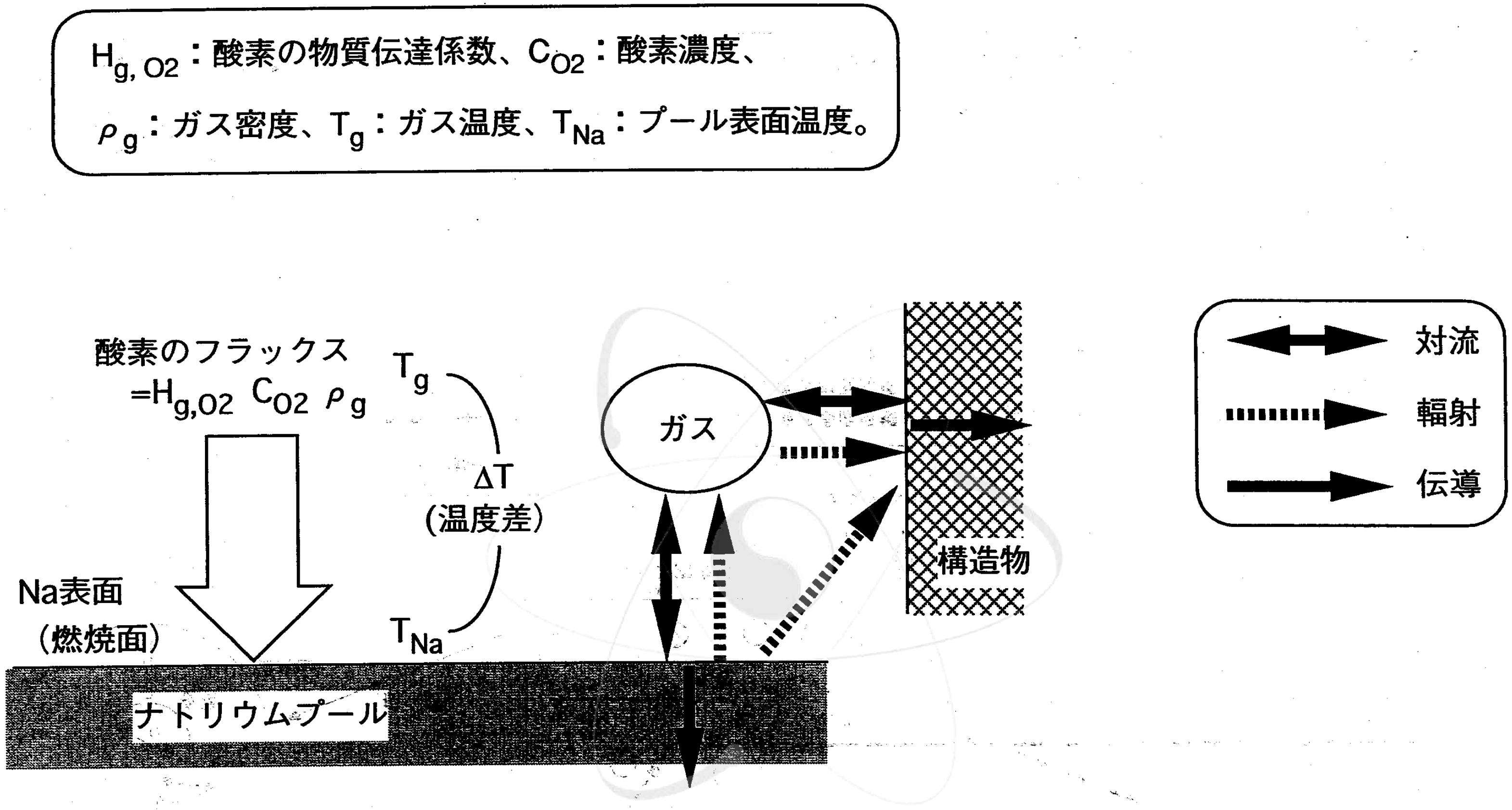
2.2.2 Calculation of pool combustion rate

Fig. 3 shows the conceptional diagram of pool combustion model. the pool combustion is assumed to be governed by oxygen supply from atmospheric gas to pool surface. Natural convection by temperature difference between the pool(burning layer) and gas atmosphere in the gas atmosphere above the pool surface where sodium burning occurs is formed. Therefore, the oxygen supply can be calculated from the analogy of natural heat and mass transfer. Fishenden-Saunders equation of eq.(9) is used as the natural convective equation of a horizontal slat.

$$Nu=0.14(Gr\cdot Pr)^{1/3} \quad (9)$$

With analogy of heat transfer and mass transfer, eq. (9) can be converted into eq.(10).

$$Sh=0.14(Gr\cdot Sc)^{1/3} \quad (10)$$



$H_{g,O2}$：酸素の物質伝達係数、C_{O2}：酸素濃度、

ρ_g：ガス密度、T_g：ガス温度、T_{Na}：プール表面温度。

Fig. 3. The conceptional diagram of pool combustion model.

From eq.(9) and (10)

Nu : Nusselt number
Sh : Sherwood number
Gr : Grashop number
Pr : Prantl number
Sc : Schmidt number

As mentioned above, Mass transfer of oxygen($H_{g,O2}$:m/s) to sodium surface is obtained by eq.(11).

$$H_{g,O2}=0.14D_{o2}(gSc\beta_g(T_{Na}-T_g)/\nu_g^2)^{1/3} \qquad (11)$$

where,

D_{o2} : Diffusion coefficient of oxygen (m^2/s)
g : Gravitational constant (m/s^2)
β_g : Volume expansion coefficient of gas (1/K)
ν_g : Kinematic viscosity (m^2/s)
T_{Na} : Surface temperature of pool (K)
T_g : Gas temperature (K)

Accordingly, the amount of oxygen is multiplied by stochiometric ratio of sodium oxygen to obtain eq.(12), sodium burning rate($B_{r,O2}$: kg-Na/m^2s)

$$B_{r,O2}=H_{g,O2}\rho_g C_{O2}\ \chi_{Na,O2} \qquad (12)$$

where,

ρ_g : Gas density (kg/m^3)
C_{O2} : Oxygen concentration (mass-fraction)
$\chi_{Na,O2}$: Stochiometric ratio (kg-Na/Kg-O_2)

Mass transfer coefficient($H_{g,H2O}$:m/s) of water vapor to sodium surface is,

$$H_{g,h2O}=0.14D_{H2o}(gSc\beta_g(T_{Na}-T_g)/\nu_g^2)^{1/3} \qquad (13)$$

where,

D_{H2o} : Diffusion coefficient of water vapor (m^2/s)

Accordingly, sodium amount is multiplied by water vapor reached to combustion plane and stoichiometric combustion ratio to obtain reaction rate of sodium with water vapor($B_{r,H2O}$: kg-Na/m^2s), which is defined as eq.(14).

$$B_{r,H2O}=H_{g,H2O}\rho_g C_{H2O}\ \chi_{Na,H2O} \tag{14}$$

where,

C_{H2O} : Concentration of water vapor (mass-fraction)

$\chi_{Na,H2O}$: Stoichiometric combustion ratio (kg-Na/Kg-H_2O)

2.2.3 Heat transfer

As can be seen from Fig. 2 and 3 SOFIRE code computes the heat transfer from sodium pool to each compartment and the heat transfer between compartments in cell. The basic equations are follow as;

(a)Natural convective heat transfer

Natural convective heat transfer rate is calculated by the following eq.(15).

$$Q_{CONVi}=h\lambda_g(gPr\beta_g(T_g-T_i)/\nu_g^{2})^{1/3}(T_g-T_i)Ai \tag{15}$$

where,

Q_{CONVi} : Convective heat transfer rate from gas to structure i (W)

h : Coefficient of convective Nu number(horizontal: 0.14, perpendicular: 0.129)

λ_g : Gas thermal conductivity (W/(mK))

T_i : Surface temperature of structure i (K)

Ai : Surface area of structure i (m^2)

(b) Radiative heat transfer

Radiative heat transfer is calculated by the following eq.(16).

$$Q_{RADij}=F\varepsilon_{ij}\ Ai(T_i^4-T_j^4)\sigma \tag{16}$$

where,

Q_{RADij} : Radiative heat transfer rate from i to j (W)

$F\varepsilon_{ij}$: Radiative heat transfer coefficient from i to j

Ai : Radiative area (m^2)

T_i^4 : Temperature of i (K)

T_j : Temperature of j (K)

σ : Stefan-Boltzmann constant(W/m^2K^4)

(c)Thermal conduction

Thermal conduction in the structure and the pool is calculated by the following eq.(17).

$Q_{CONDij}=K_{ij}A_{ij}(T_i-T_j)$ (15)

where,

Q_{CONDij} : Conductive heat transfer rate from i to j (W)
A_{ij} : Area(m^2)
T_i : Temperature of i (K)
T_j : Temperature of j (K)
K_{ij} : Gas thermal conductivity from i to j (W/m^2K)

(d) Consideration of accumulation of reactants on the pool

There are sodium, sodium monoxide, sodium peroxide, sodium hydoxide in the pool. The amount of reactants which is accumulated on the pool varies as the combustion behavior. Accumulation model of reactants can be treated in same manner that the heat transfer from thickness of reactants to the floor, which is calculated by pool combustion is corrected. The heat transfer from sodium to the pool is expressed by eq.(18), which the heat transfer rate from thickness of reactants to the floor is corrected.

$$Q_{pool-floor}=A\left(\frac{X_{Na}}{K_{Na}}+\frac{X_{Na_2O_x}}{K_{Na_2O_x}}+\frac{X_{floor}}{K_{floor}}\right)^{-1}(T_{Na}-T_{floor}) \qquad (18)$$

where,

A : pool area(m^2)
X_{Na} : 1/2 of sodium height(m)
k_{Na} : Thermal conductivity of sodium (W/mK)
X_{Na2Ox}^* : 1/2 of reactants (m)
k_{Na2Ox}^* : Thermal conductivity of reactants (W/mK)
x_{floor} : 1/2 of floor thickness (m)
k_{floor} : Thermal conductivity of floor (W/mK)
T_{Na} : Pool temperature (K)
T_{floor} : Floor temperature (K)
*, subscript means the sum of Na_2O, Na_2O_2, and NaOH

2.2.4 Temperature calculation of each compartment

Gas temperature in each cell(1-cell, 2cell) is treated identically. Also one-dimensional temperature distribution in direction of depth for structure(floor, wall, roof) is calculated. But the heat balance by heat transfer is considered for this calculation.

(a) Temperature rate on the surface

$dT_1/dt=(Q_{g,1}+Q_{R,1}-Q_{D,1})/(C_{p1}d_1A_1\rho_1)$ (19)

where,

$Q_{g,1}$: Convective heat transfer rate between gas and structure (W)
$Q_{R,1}$: Radiative heat transfer rate between gas and structure (W)
$Q_{D,1}$: Heat transfer rate by heat conduction (W)
C_{p1} : Specific heat of structure at constant pressure (J/kgK)
d_1 : Thickness of structure surface(the first mesh) (m)
A_1 : Surface area of structure (m^2)
ρ_1 : Density of structure (kg/m^3)

(b) Temperature change rate into structure to node(mesh) i

$$dT_1/dt=(Q_{D,i-1}+Q_{,D,i})/(C_{pi}d_iA_i\rho_i) \quad (20)$$

where,

$Q_{D,i-1}$: Convective heat transfer rate from i (W)
$Q_{D,i}$: Convective heat transfer rate to i (W)
C_{pi} : Specific heat of structure at constant pressure (J/kgK)
d_i : Thickness of structure section(node) (m)
A_i : Surface area of structure (m^2)
ρ_i : Density of structure (kg/m^3)

(c) Dependence of structure on temperature

The thermal conductivity and the specific heat of structure(floor, roof, liner, insulator etc.) can be considered to be dependent on temperature. Accordingly, they are capable of being specified as input with table format.

2.2.5 Evolution of water vapor from the concrete

The amount of evolution of water vapor from the concrete is specified in the input, with a table specifying the relation of ratio of concrete temperature to water vapor release. And then, water vapor equivalent to a portion of temperature rise is released. For example, when the temperature of concrete increases from T1 to T2, the weight of concrete decreases from M1 to M2. The water vapor equivalent to a decrease portion of concrete weight is released. Because water vapor release once is assumed to come out of the concrete, the difference of temperature for the computation of water vapor becomes the difference from the highest of temperatures till that time.

The amount of evolution of water vapor(W;kg) is calculated by the following equation.

$$W=(M_{new}-M_{old})A_{con}X_{con}\rho_{con} \quad (21)$$

where,

A_{con} : Area of concrete (m^2)
X_{con} : Mesh thickness of concrete (m)
ρ_{con} : Density of concrete (kg/m^3)
T_{old} : Peak temperature to previous step (K)
T_{new} : Temperature of concrete (K)
M_{old} : Weight ratio reduced to previous step (-)
M_{new} : Number of tables for weight reduction ratio of concrete

The above eq.(21) is the computation equation at one node of the concrete, but it is calculated and integrated for each node of all the concrete in each cell to calculate the release of water vapor to gas atmosphere in each cell.

2.2.6 Gas pressure

Gas density and gas temperature is calculated. And then gas pressure in each cell(1-cell, 2-cell) is calculated from ideal gas equation, being assumed to be the same.

$$P_g=R\rho_g T_g/M_g \tag{22}$$

where,

R : Gas constant (J/molK)
ρ_g : Gas density (kg/m3)
T_g : Gas temperature (K)
M_g : Molecular weight of gas (kg/mol)

2.2.7 Flow between cells

It is possible to consider three kinds of flows between each cell(1-cell, 2-cell, 3-cell) as follows.

- Gas leak model
- Convective flow model
- Pressure balance flow model

Each model is described below.

(a) Gas leak flow

Reference pressure and gas leak rate are specified in input, and the gas leak flow rate is calculated by gas leak flow model.

$W_{LEAKk,l}=RL_{k,l}(\Delta P_{k,l}/PD_{k,l})^{1/2}\rho_k$ (23)

where,

$W_{LEAKk,l}$: Gas leak flowrate from room k to room l (kg/s)

$RL_{k,l}$: Gas leak ratio from room k to room l (m^3/s)

$\Delta P_{k,l}$: Pressure difference between room k and room l (Pa)

$PD_{k,l}$: Reference pressure for the computation of room k and room l (Pa)

ρ_k : Density of room k (kg/m^3)

(b) Convective gas flow

Cross-sectional area and thickness, diameter of flow path between cells, diameter is determined by convective gas flow model, and then gas flowrate between cells is calculated. A direction of convective gas flow is divided into perpendicular gas flow and horizontal convective gas flow according to the location of each cell.

- Perpendicular gas flow

$W_{CONVk,l}=V_{k,l}A_{k,l}\rho_{gk}$ (24)

where,

$W_{CONVk,l}$: Convective flow rate from k to l(kg/s)

$V_{k,l}$: Convective flow velocity from k to l determined by Brown empirical equation (m/s)

$V_{k,l}$ is the unit of (ft/h), and calculated by eq.(25).

$V_{k,l}=0.07753/X_{k,l}(D_{k,l}/X_{k,l})^{1/3}\alpha_{gk}(X_{k,l}{}^3 g\beta_k|T_{gk}-T_{gl}|/\upsilon_k{}^2)^{0.55}$ (25)

where,

$X_{k,l}$: Height of cross section of flow path between room k and room l (ft)

$D_{k,l}$: Horizontal width of cross section of flow path between room k and room l (ft)

α_{gk} : Thermal diffusion rate of room (ft^2/h)

β_k : Gas volume expansion coefficient of room k (1/K)

υ_k : Gas kinetic viscosity of room (ft^2/h)

T_{gk}, T_{gl} : Gas temperature of room k and room l (K)

In addition, flowrate from l to k is calculated by eq.(26).

$W_{CONVl,k}=V_{k,l}A_{k,l}\rho_{gl}$ (26)

- Horizontal convective gas flow

Gas transfer rate of two cells located horizontally is calculated by eq.(27).

$$W_{CONVk,l} = C/3(g\beta\Delta T)^{1/2}WH^{3/2}\rho_{gk} \qquad (27)$$

where,

C : Orifice coefficient (-): input value
g : Gravitational constant (m/s^2)
β : Volume expansion coefficient (1/K)
ΔT : Temperature difference between cells (K)
W : Horizontal cross-sectional thickness of of flow path (m)
H : Cross-sectional height of flow path (m)

In addition, flowrate from 1 to k is calculated by eq.(28).

$$W_{CONVl,k} = C/3(g\beta\Delta T)^{1/2}WH^{3/2}\rho_{gl} \qquad (27)$$

(c) Pressure balance flow

Pressure balance flow rate model is treated by pressure balance flow model in the same manner that the pressure of two cell become to attain their equal value. For example, in the case of Pk>Pl, the gas flows from k to l to become Pk=Pl.

(d) Treatment of the other gas function

ASSCOPS is capable of computing the following gas flows, in addition to gas leak, convective flow, and pressure balance flow as described above.

- Gas ventilation(inflow) from the outside to each cell(1-cell, 2-cell)
- Gas exhaust from each cell(1-cell, 2-cell) to the outside
- Gas exhaust by pressure release plate

Gas ventilation(inflow) into each cell and gas exhaust to the outside is specified in the input with ventilation(exhaust) tabulated. Gas exhaust by the open and the shut of the pressure release plate uses a model which it is opened and shut in the case of the rise of the pressure in cell. The setting pressure for the open and the shut of the pressure release plate and the gas flow rate through pressure release plate is tabulated and specified in the input. The setting time and flowrate of nitrogen blow is tabulated and specified in the input.

2.2.8 Settling transfer calculation of aerosol

Aerosol between cells is transferred by instant mixture of aerosols in each cell with different concentration. Flowrate between cells is calculated by eq.(29).

$ANA_n = WNA_n dW_{gas} / W_{gas} dt$ (29)

where,

ANA_n : Transfer rate of aerosol with mass transfer number n between cells (kg)

WNA_n : Amount of aerosol with mass transfer number n in cell (kg)

dW_{gas} : Flow rate of gas between cells (kg/s)

W_{gas} : Gas weight between cells (kg)

dt : Time step (s)

Aerosol settling is treated by the gravitational settling model, and calculated by eq.(31), and (32).

$dn/dt = nv/h$ (30)

where,

dn/dt : Falling velocity (unit/s)

n : Number of particle (unit)

v : Falling velocity of particle(m/s)

h : Falling height(Input: 1/2 of cell height) (m)

$v = \rho d^2 g / 18\eta$ (31)

where,

ρ : Density(kg/m^3)

d : Average diameter(m)

g : Gravitational acceleration(m/s^2)

η : Gas viscosity(Pa · s)

$n = w/(\pi/6 d^3 \rho)$ (32)

where,

w: Total mass(kg)

Viscosity of gas is the function of temperature. Also, aerosol is assumed to be deposited homogeneously. And Settling amount to the pool is calculated by the ratio of the floor area to the pool area, which is specified in the input.

2.2.9 Reaction of aerosol with water vapor

Sodium oxide(Na_2O, Na_2O_2) of aerosol floating in gas atmosphere react to water vapor by eq.(6) and (7) as described above. Aerosol-water vapor reaction model based on the diffusion of water vapor is considered to obtain the reaction rate. If water vapor in gas atmosphere diffuses aerosol particles and react to them, the reaction rate is expressed by the diffusion equation of eq.(33)

$$dM_{H2O}/dt=\Phi_{H2O}N \tag{33}$$
$$\Phi_{H2O}=4\pi rD_{H2O}(\rho_{H2O,a}-\rho_{H2O,r})X \tag{34}$$

where,
dM_{H2O}/dt : Reaction rate of aerosol with water vapor (kg-H_2O/s)
N : Number of aerosol(N)
Φ_{H2O} : Mass flux per a aerosol particle (kg-H_2O/N/s)
r : Radius of aerosol particle (m)
D_{H2O} : Diffusion coefficient of water vapor (m^2/s)
$\rho_{H2O,a}$: Density of water vapor in atmosphere((kg-H_2O/m^3)
$\rho_{H2O,r}$: Correction for average free distance near particle surface (-)
$X=1/(1+(0.71+(4/3)Kn)Kn/(1+Kn)$
$Kn=lg/r$: Knudsen number
lg : Average free distance of air molecule (m)

Water vapor is reacted and consumed($\rho_{H2O}=0$). Because average free distance of air molecule is $6x10^{-8}$m(at 20℃)~$15x10^{-8}$m(at 300℃) or so, it comes to $Kn<1.0$, $X\fallingdotseq 1$. And eq.(34) is expressed approximately by eq.(37).

$$\Phi_{H2O}=AC_{H2O}$$

where,
A : Reaction rate coefficient{$=4\pi rD_{H2O}(\rho_{gas}$}(kg-$H_2O$/N/s)
C_{H2O} : Weight concentration of water vapor in atmosphere($=\rho_{H2O,a}/\rho_{gas}$) (kg-H_2O/kg-gas)
ρ_{gas} : Density of atmosphere gas(kg-gas/m^3)

2.2.10 Computation of the other heat generation and cooling

ASSOCOPS treats the sodium combustion, the reaction of sodium with water vapor, the reaction of sodium oxides with water vapor and generation of heat by the evolved hydrogen. In addition, it deals with such the generation of heat as;

- Heat generation by gamma(γ)ray
- Heat generation by fission product(FP)
- Generation of heat(cooling) which generation rate of heat(cooling) is constant
- Generation of heat(cooling) which generation rate of heat(cooling) is dependent on

temperature

Models about the generation of heat(or cooling) is described from now on.

(a) Generation of heat by gamma(γ) ray

Gamma(γ)ray is assumed not to be moved and $Q_r(i,k)$(W), heat generation rate by gamma(γ)ray from room k to l is expressed by eq.(38).

$$Q_r(i,k)=R_\gamma(i,k)Q_r(0)K\exp(-(\ln 2/t^{1/2})t) \tag{38}$$

where,

$R_\gamma(i,k)$: Distribution coefficient of heat generated by gamma(γ)ray in room k room and room I (-) ≦1

$Q_r(0)K$: Generation rate of heat by initial total gamma ray to cell k (W)

$t^{1/2}$: Half life of gamma source(h)

k : : Cell number(1-cell in the case of k=1, 2-cell in the case of k=2)

i : Node number of each cell

In addition,

$$\sum_i R_\gamma(i,k)=1.0$$

(b) Generation of heat by fission product(FP)

Fission product is in existence in the gas atmosphere. Ray source accompanied by the move of gas between cells is considered as same as the move of aerosol. Concentration of fission product(C_{FRK}) in gas atmosphere of each cell at each time is used to obtain the heat generation($Q_{FP}(i,k)$(W)) at position i of cell k of eq.(39).

$$Q_{FP}(i,k)=C_{FPK}W_{gas}(k)q_{FP}(t)R_{FP}(i,k) \tag{39}$$

where,

$C_{FPK}W_{gas}(k)$: The amount of fission product(FP) of cell k (kg)

$q_{FP}(t)$: Generation rate of heat per the unity of FP (W/kg)

$R_{FP}(i,k)$: Distribution coefficient for the generation of heat of FP at position i of cell k

k : Cell number(1-cell in the case of k=1, 2-cell in the case of k=2)

I : Node number of each cell

In addition,

$\sum_i R_{FP}(i,k)=1.0$

(c) Generation of heat(cooling) which generation rate of heat(cooling) is constant

$$Q_h(i,k)=Q_h^*(i,k) \qquad (40)$$

where,

$Q_h^*(i,k)$: Generation rate of heat at position i of cell k(negative value in the case of cooling) (W)
; Input value
k : Cell number(1-cell in the case of k=1, 2-cell in the case of k=2)
I : Node number of each cell

(d) Generation of heat(cooling) which generation rate of heat(cooling) is dependent on temperature

$$Q_c'(i,k)=\alpha_h(i,k)[T(i,k)-T_{in}(i,k)] \qquad (41)$$

where,

$\alpha_h(i,k)$: Heat generation(or cooling) coefficient at position i of cell k (W/K)
$T(i,k)$: Temperature at position i of cell (K)
$T_{in}(i,k)$: Temperature of heat source(or cooling) (K)
k : Cell number(1-cell in the case of k=1, 2-cell in the case of k=2)
I : Node number of each cell

In addition, in the case of $\alpha_h(i,k)<0$, it comes to $Q_c'(i,k)<0$. Therefore the position i of cell k is heated as much as the very quantity of heat. Differently from this, in the case of $\alpha_h(i,k)>0$, it comes to $Q_c'(i,k)>0$ Therefore the position i of cell k is cooled as much as the very quantity of heat.

2.3 SPRAY model

SPRAY model treats mainly 2-cell. As can be seen from Fig. 2, it deals with the spray combustion by the pipe breaks, the reaction and combustion of sodium with water vapor, and also the pool combustion, the reaction and combustion of sodium with water vapors, same as SOFIRE module. And it computes the change of the temperature and the pressure. Fig. 4 shows a concept of the heat transfer resulting from spray combustion. Also pool combustion model, which SPRAY treats, is the same as SOFIRE module.

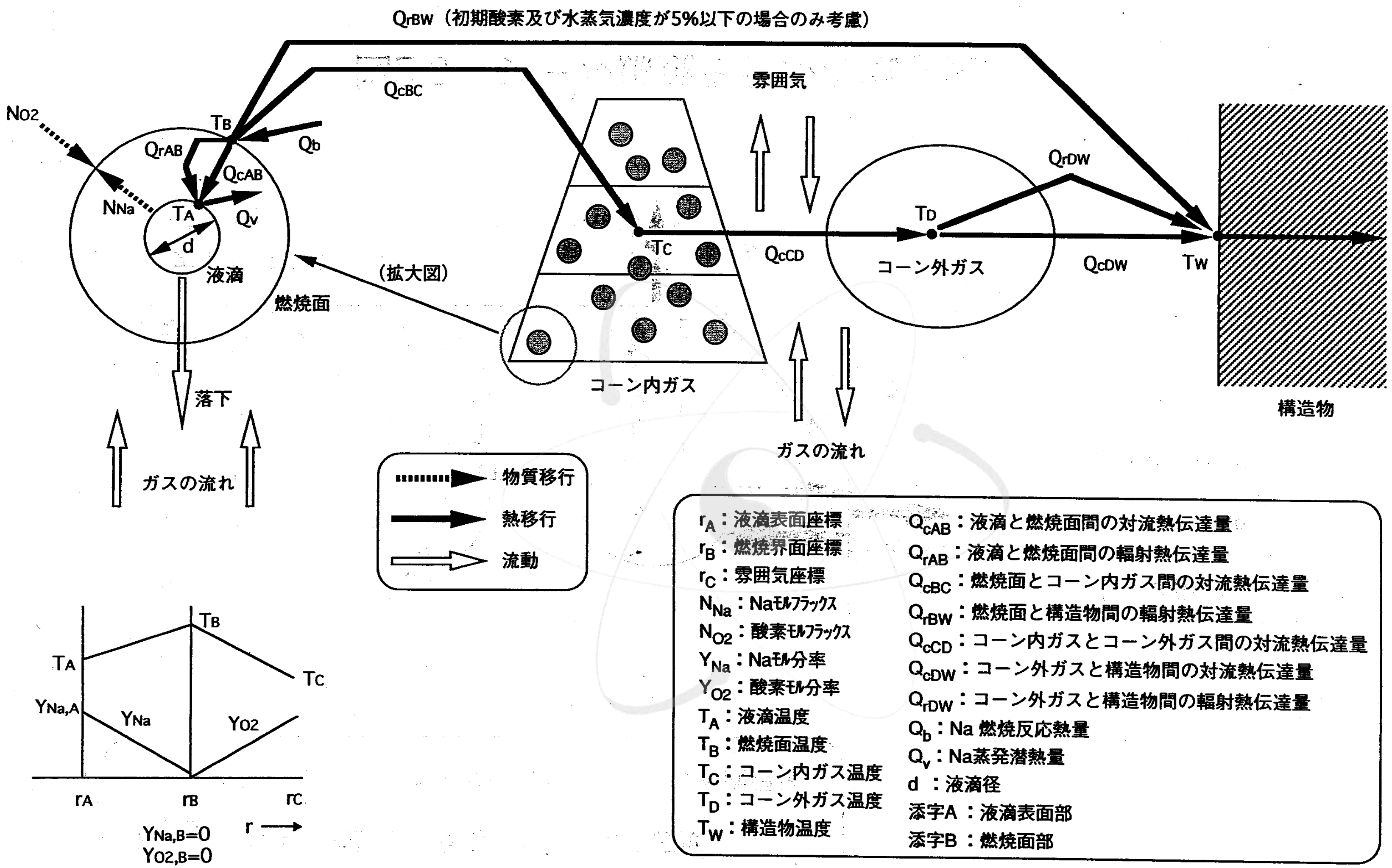


Fig. 4. A concept of the heat transfer resulting from spray combustion.

2.3.1 Chemical reaction

There are two major chemical reactions possible for sodium spray combustion.

$2Na(g)\ +1/2O_2(g)\rightarrow Na_2O(s)$ △h= -634kJ/mol-Na_2O (42)

$2Na(g)\ +O_2(g)\rightarrow Na_2O_2(s)$ △h= -731kJ/mol-Na_2O_2 (43)

Ratio of eq.(42) and (43), which is dependent on oxygen concentration, is the same as that of pool combustion in SOFIRE module and specified as input.
There are three sodium-water reactions for sodium spray.

$2Na(g)+H_2O(g)\rightarrow Na_2O(s)+H_2(g)$ △h= -394kJ/mol-Na_2O (44)

$Na(l)+H_2O(g)\rightarrow NaOH(s,l)+1/2H_2(g)$ △h= -291kJ/mol-NaOH (45)

$4Na(g)+H_2O(g)\rightarrow Na_2O(s)+2NaH(s,l)$ △h= -715kJ/mol-Na_2O (46)

Ratio in eq. (44), (45) and (46) cab be specified as input.
It is assumed that Sodium monoxide, sodium peroxide and sodium hydoxide generated by spray combustion and reaction of sodium with water vapor(eq.(42), (43), (44), (45) and (46)) all is released in gas atmosphere. Reaction of aerosol with water vapor already has been described above by SOFIRE module(section 2.2.9). Also, hydrogen generated by eq.(44) and (45) is in existence as much as oxygen, same as SOFIRE module. At the same time, in case that sodium continues to burn, hydrogen reacts to oxygen as eq.(8).

$H_2(g)+1/2O_2(g)\rightarrow H_2O(g)$ △h= -242kJ/mol-H_2O (8)

Ratio of hydrogen and lower limit of oxygen concentration required for reaction of eq. (8) is specified by input in the same manner as SOFIRE module.
In addition, Sodium combustion model used in SPRAY module is identical to that in used in SOFIRE module.

2.3.2 Spray model

Spray model assumes that the surrounding of droplet is burning layer. which reach burning layer and from the atmosphere is determined by eq.(51) and (52). The burning rate is calculated by the mole flux(N_{Na}) of Na diffused from droplet surface to burning layer and (N_{O2}) of oxygen diffused from gas atmosphere to burning layer. Because spray droplet is falling down, the burning rate is computed from the analogy of the forced convective heat transfer of droplet and the mass transfer. Nusselt number(Nu) and Sherwood number is obtained by eq. (47), (48).

$Nu=2+0.6(Re^{1/2}Pr^{1/3})$ (47)

$Sh=2+0.6(Re^{1/2}Sc^{1/3})$ (48)

Mole flux $N_{Na}(mol/m^2s)$ for the distance between sodium droplet surface and burning layer is expressed by eq.(49).

$N_{Na}=(r_A/r^2)/(1/r_A-1/r_B)K_{Na}\ln(1-Y_{Na,B})/(1-Y_{Na,A}))$ (49)

where,

r : Radius (m)

K_{Na} : Mass transfer coefficient (mol/m^2s)

$Y_{Na,A}$: Mole fraction (-)

Subscript Na : Na

Subscript A : Droplet surface

Subscript B : Burning layer

In the case of sodium vapor, $N_{Na,A}$ is obtained by setting r=r in eq. (49). Then W_{Na} is obtained by eq.(50).

$W_{Na}=4\pi r_A^2N_{Na}=4\pi r_A/(1/r_A-1/r_B)K_{Na}\ln(1/(1-Y_{Na,A}))$ (50)

Also, the flux(W_{O2}, W_{H2O}) which reach burning layer from the atmosphere is determined by eq.(51) and (52).

$W_{O2}=4\pi r_A^2N_{O2}=4\pi r_A/(1/r_B-1/r_C)K_{O2}\ln(1/(1-Y_{O2}))$ (51)

$W_{H2O}=4\pi r_A^2N_{H2O}=4\pi r_A/(1/r_B-1/r_C)K_{H2O}\ln(1/(1-Y_{H2O}))$ (52)

where,

Subscript O2 : Oxygen

Subscript H2O : Water vapor

Subscript C : Atmosphere

This flux results from reaction on the burning layer. Therefore stochiometric ratio (χ) is used to obtain mass balance equation of eq.(53).

$W_{Na}=\chi_{O2}W_{O2}+\chi_{H2O}W_{H2O}$ (53)

where, W_{Na} can be expressed by the burning rate(Br_{Na}).
Also, The following heat balance is established for droplet and burning layer.

- Droplet : $m_{Na}Cp_{Na}(dT/dt)=-Q_vW_{Na}+Q_{AB}$ (54)
- Burning layer : $W_{Na}Q_b+Q_{AB}=4\pi r_B^2h(T_B-T_C)+4\pi r_B^2\varepsilon\sigma(T_B^4-T_W^4)$ (55)

where,

m_{Na} : Mass of droplet (kg)
Cp_{Na} : Specific heat of Na (J/kgK)
Q_v : Latent heat of vaporization of Na (J/kg)
Q_b : Combustion reaction heat (J/kg)
T_A : Temperature of droplet (K)
T_B : Temperature of burning layer (K)
T_C : Gas temperature inside spray cone (K)
T_W : Temperature of wall (K)
Q_{AB} : Heat transfer rate between droplet and burning layer (W)
h : Heat transfer coefficient to the surrounding gas (W/m^2K)
ε : Constant of emissivity (-)
σ : Stefan-Biltzmann constant (W/m^2K^4)

Q_{AB} and h is defined by eq.(56) and (57), respectively.

$$Q_{AB}=4\pi r_Ar_Bh(T_A-T_B)+4\pi r_A^2\varepsilon\sigma(T_A^4-T_B^4) \quad (56)$$

$$h=\lambda_g(2+0.6(Re^{1/2}Pr^{1/3}))/d \quad (57)$$

where,

λ_g : Thermal conductivity (W/mK)
Re : Reynolds number (-)
Pr : Prandtl number (-)

By analysing simultaneously the above equations, the position(r_B) and the temperature(T_B) of burning, and the burning rate($W_{Na}=Br_{Na}$) is calculated.

2.3.3 Calculation of heat transfer

The space of 2-cell is divided into the inside area of spray cone and the outside area of spray cone. The spray region is divided by arbitrary number of meshes(number of meshes being specified in the input), and the droplet temperature, droplet diameter and gas temperature is calculated. The heat source and the heat transfer for the spray combustion consider such items as;

1. Generation rate of heat by chemical reaction eq. (42), (43), (44), (45), (46), (8)
2. Heat transfer rate between droplet and burning layer(Q_{AB}; eq.(56))
3. Latent heat of vaporization to the droplet surface
4. Convective heat transfer between the gas inside spray cone and burning layer(Q_{cBC})

$$Q_{cBC}=4\pi r_B h(T_B-T_C) \tag{58}$$

where, h is defined by eq.(57) as explained above.

5. Radiative heat transfer between burning zone and wall(Q_{rBW})

$$Q_{rBW}=4\pi r_A r_B^2 \varepsilon_{BW} \sigma (T_B^4-T_W^4) \tag{59}$$

where, ε_{BW} : Radiation coefficient from burning zone

In addition, (Q_{rBW}) is considered in case that the concentration of aerosol in gas atmosphere is low.

6. Convective heat transfer between gas and wall(Q_{cDW})

Because the convection of gas is formed in gas atmosphere, at the very first Nu is determined by Sparrow-Gregg criteria as shown in table 1.

Table 1. Criteria of Sparrow-Gregg.

0.225Re2>Gr			
Yes(Forced convection)		No(Natural convection)	
Re>4x10^5		Re>10^5	
No	Yes	No	Yes
Laminar flow $Nu=0.664Re^{1/2}Pr^{1/3}$	Turbulent flow $Nu=0.037Re^{0.8}Pr^{1/3}$	Laminar flow $Nu=0.021Ra^{0.25}$	Turbulent flow $Nu=0.021Ra^{0.4}$

In addition, Reynolds number(RE), Grashof number, and Ra is defined by eq. (60), (61), (62).

$$Re=U_D H/\nu_g \tag{60}$$

$$Gr=g\beta H^3(T_D-T_W)/\nu_g^2 \tag{61}$$

$$Ra=GrPr \tag{62}$$

where,

U_D : Average velocity of gas in the outside cone (m/s)

H : Characteristic length (m)

ν_g : Kinetic viscosity (m^2/s)
g : Gravitational constant (m/s^2)
β : Volume expansion coefficient (1/K)
T_D : Gas temperature of gas in the outside cone (K)
T_W : Wall temperature of wall (K)

From the above equations, convective heat transfer coefficient(h;W/m^2K) from gas to wall will be eq.(63).

$$h=\lambda_g Nu/H \tag{63}$$

Therefore, convective heat transfer rate(Q_{cDW}) from gas to wall is obtained by eq.(64).

$$Q_{cDW}=h\lambda_g(gPr\beta_g(T_D-T_W)/\nu_g^2)^{1/3}(T_D-T_W)A_W \tag{64}$$

where,
A_W : Surface area of wall (m^2)

2.3.4 Falling droplet motion of sodium

Droplet trajectory is considered in the vertical direction only since the horizontal component is small and has minor effect on droplet velocity. Vertical motion may be calculated by summing the gravitational, droplet drag, buoyancy and mass rate of change forces. Therefore u(m/s), velocity of droplet is expressed by eq.(65).

$$du/dt=g-3/4(u^2C_D/d)(\rho_g/\rho_{Na})$$
(65)

where,
g : Gravitational acceleration (m/s^2)
C_D : Drag coefficient
d : Droplet diameter (m)
ρ_g : Gas density (kg/m^3)
ρ_{Na} : Sodium droplet density (kg/m^3)

2.3.5 Interaction of gas and droplet

The space of 2-cell is divided into the inside area of spray cone and the outside area of spray cone as described in the heat transfer calculation model. It is considered that there are the inside gas of spray cone and the outside gas of spray cone, which contribute to the convective heat transfer in the inside area of spray cone and the outside area of spray cone, respectively. Gas motion is determined by summing the force of thermal buoyancy(f_b), droplet drag(f_d), flow friction(f_{fr}). In addition, Thermal buoyance imposes an upward force on the hot spray zone gases due to the cool outer region. Droplet dray applies a downward force to the spray zone gases.

$$d(mv)/dt=f_b-f_d\pm f_{fr} \tag{66}$$

3. Analyses of sodium leak and fire accident for KALIMER

3.1 ASSCOPS's sodium fire model for KALIMER

The buildings and structures comprising the KALIMER plant as shown in Fig. 5 are divided into two categories; safety related and BOP. The safety related buildings and structures are such as the reactor building, the fuel handling and storage building, the radio active handling building, and the health physics building. They are located within the high security boundary. The BOP buildings and structures are such as the control building, the T/G building, the maintenance building, warehouse, pump house, condensate storage tanks, transformers, and switchyard etc.. The dimension of reactor building is in 39m(W) x 52m(L) x 56.8m(H).

The steam generators are located at both sides of reactor and the S/G dump tanks are just below the SGs. There is an insulated catch pan with suppression deck under the dump tank which collects the spilled sodium. A schematic representation of S/G building including ASSCOPS's sodium fire model is shown in Fig. 6. A series of calculations is performed for evaluating the sodium leak and fire accident in S/G building. The dimension of S/G building is in 16m(W) x 24m(L) x 35m(H). ASSCOPS's sodium fire model for S/G building consists of two cells. The lower part of S/G building is defined as the 1-cell in which the sodium pool fire occurs. And the upper part of S/G building which is connected to 1-cell by opening is defined as the 2-cell, which both the sodium spray fire and the sodium pool fire occur. The floor, the roof, and the wall of each cell is covered with the steel liner. Structures in each cell consist of the steel liner, the insulator, and the concrete different in the thickness as shown Fig. 6.

The ventilation openings are placed on the sidewall of building so that air is ventilated from the outside to each cell(1-cell, 2-cell) and exhausted, and nitrogen gas is injected from the gas control system. It is postulated that spray zone is formed by rain down of droplet from sodium jet impact area on the ceiling of 2-cell. It is postulated that sodium fall down at 23-m high from the floor of 2-cell. If any sodium leak accident occurs in the S/G building, it is modeled so that sodium on the floor of 2-cell, which is sprayed from sodium jet impact area on the ceiling, flows into the floor of 1-cell and then drain into the dump tank through the sodium drain pipe. The pressure release plate is to be installed on the sidewall of each cell so that the building is protected from the excessive rise of the pressure or the negative pressure due to the thermodynamic consequence of the fire in the cell. The setting pressure for the open and the shut of the pressure release plate and the gas flow rate through pressure release plate is tabulated and specified in the input.

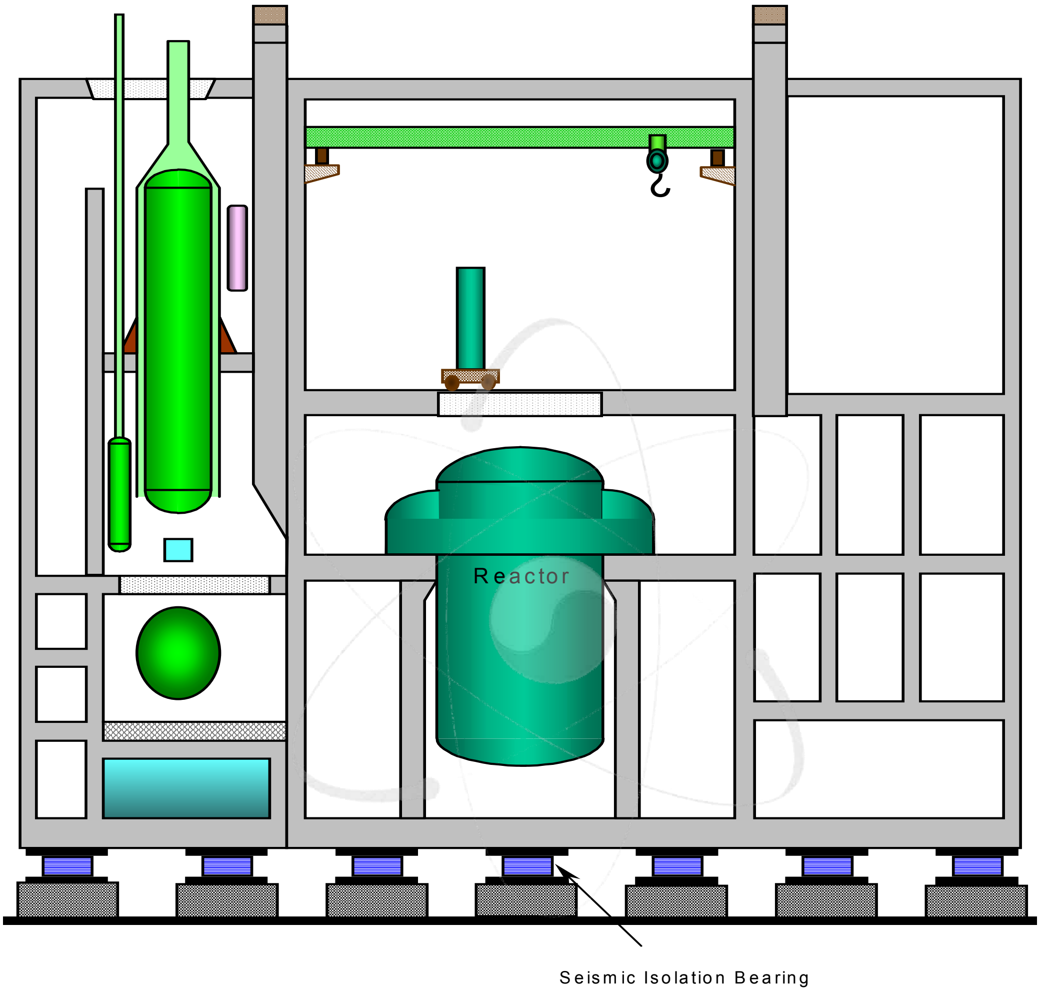


Fig. 5. Overall drawing of KALIMER reactor structures.

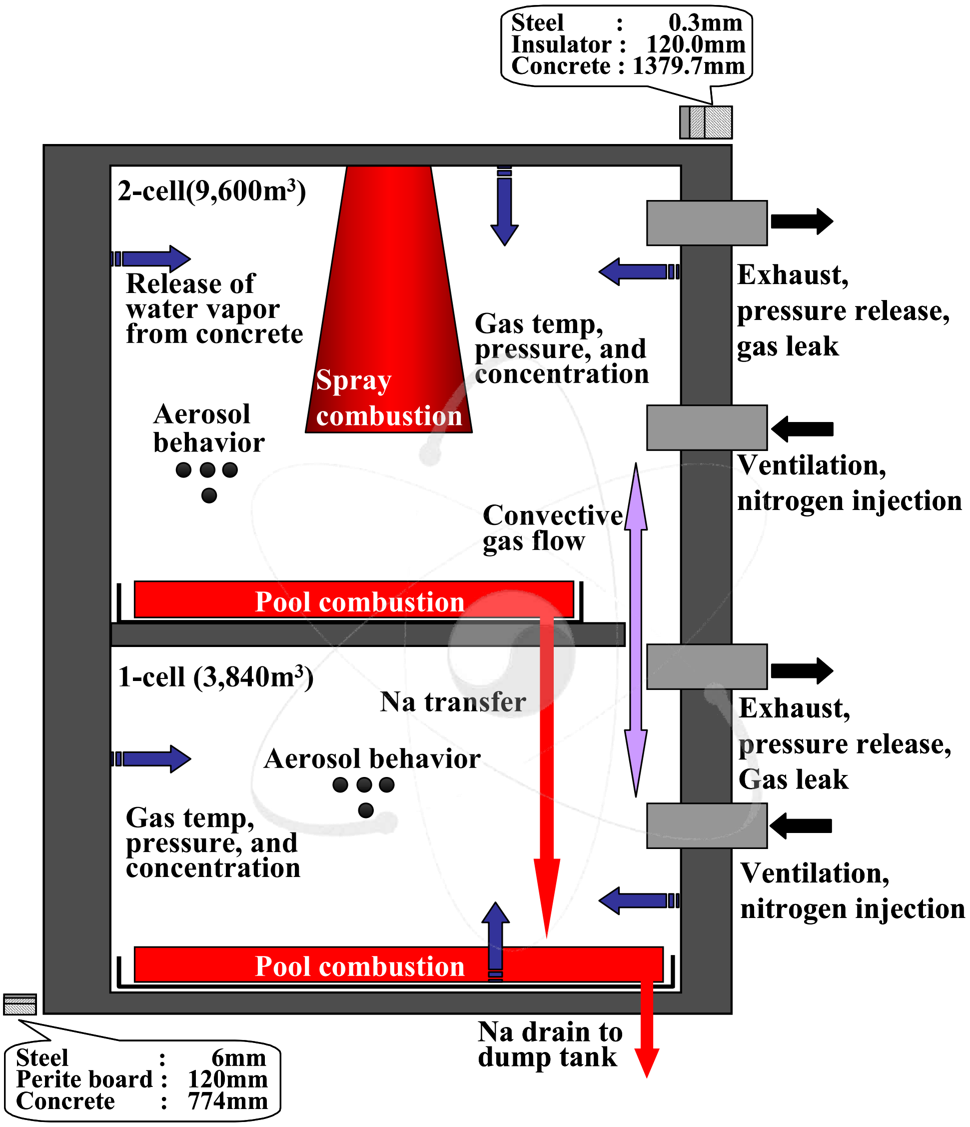


Fig.6. ASSCOPS s sodium fire model in S/G building.

The computation conditions from Run 1 to Run 36 for simulating the sodium leak and fire accident in S/G building of KALIMER are summarized in Table 2 and 3. And the thermochemical properties of the structures is shown in Table 4.

Table 2. General calculation conditions.

Cell volume(m^3)		Initial oxygen concentration (%)	Initial temperature of gas atmosphere and structures(℃)	Initial pressure of each cell (kPa)	Sodium pool temperature (℃)	Cross-sectional flow path area between 1-cell and 2-cell(m^2)
1-cell	2-cell					
3840	9600	18.8	30	101.3	500	5.0

Table 4. Thermochemical properties of structures.

Substance	Density(kg/m^3)	Thermal conductivity (W/m · K)	Specific heat(KJ/kg · K)
Carbon steel	7800.0	43.600	0.607
Concrete	2300.0	1.840	1.050
Perlite board(insulator)	180.0	0.106	1.260
FFLX(insulator)	170.0	0.078	1.150
Stainless steel	9800.0	43.600	0.607

3.2 Results and discussion

3.2.1 Effect of sodium leak rate

Fig.7, 8, and 9 present the transients of the calculated pressure, temperature, and oxygen concentration in cases when the sodium leak rate is 0.1, 5.0, 10.0, 20.0, and 30.0kg/sec. The code postulates the pressure balance flow between 1-cell and 2-cell. Consequently, the pressure in 1-cell appears to be exactly the same as that in 2-cell as shown in Fig. 7. The Fig. 7 shows that the peak pressures become higher as the sodium leak rate increases, and the leak rate has significant effect on gas pressure in cell. At leak rate of 30.0kg/sec, the pressure increases rapidly with the time, up to maximum(18,380Pa) in 0.00529hr after the initiation of the leak, and then quickly decreases up to 3,000Pa, at which pressure release plate opens. Thereafter the pressure has negative value, and the pressure decreases with the time, and then increases at a

Table 3. Summary of calculation conditions

Run No.	Initial oxygen conc.(%)	sodium leakage		Gas leak flowrate from 1-cell, 2-cell to the atmosphere, respectively(m^3/hr)	ventilation flowrate from 1-cell, 2-cell to the atmosphere, respectively(m^3/hr)	exhaust flowrate from 1-cell, 2-cell to the atmosphere, respectively(m^3/hr)	N_2 injection flowrate from 1-cell, 2-cell to the atmosphere, respectively (m^3/hr)	Gas flowrate from 1-cell, 2-cell to the atmosphere at each differential pressure(kPa), (m^3/hr)			Sodium drain to dump tank	Remark
		rate (kg/h)	duration (hr)					-0.1	3.01	100.1		
1	18.8	30.0	0.5	3×10^3, 1×10^2	-	-	-	0, 0	$2x10^3$, $2x10^3$	$2x10^3$, $2x10^3$	Not drained	
2	20.9	30.0	0.5	3×10^3, 1×10^2	-	-	-	0, 0	$2x10^3$, $2x10^3$	$2x10^3$, $2x10^3$	Not drained	
3	20.9	30.0	0.5	3×10^3, 1×10^2	-	-	-	0, 0	0, 0	$2x10^3$, $2x10^3$	Not drained	
4	20.9	30.0	0.5	0, 0	-	-	-	0, 0	0, 0	$2x10^3$, $2x10^3$	Not drained	
5	20.9	30.0	0.1	3×10^3, 1×10^2	-	-	-	0, 0	$2x10^3$, $2x10^3$	$2x10^3$, $2x10^3$	Not drained	Calculation time of 0.5hr
6	20.9	30.0	0.5	3×10^3, 1×10^2	-	-	-	0, 0	$2x10^3$, $2x10^3$	$2x10^3$, $2x10^3$	Drained	IOPTIN≠0
7	20.9	30.0	0.5	3×10^3, 1×10^2	-	-	-	0, 0	$2x10^3$, $2x10^3$	$2x10^3$, $2x10^3$	Drained	IOPTIN=0
8	20.9	5.0	0.5	3×10^3, 1×10^2	-	-	-	0, 0	$2x10^3$, $2x10^3$	$2x10^3$, $2x10^3$	Not drained	
9	20.9	10.0	0.5	3×10^3, 1×10^2	-	-	-	0, 0	$2x10^3$, $2x10^3$	$2x10^3$, $2x10^3$	Not drained	
10	20.9	20.0	0.5	3×10^3, 1×10^2	-	-	-	0, 0	$2x10^3$, $2x10^3$	$2x10^3$, $2x10^3$	Not drained	
11	20.9	0.1	0.5	3×10^3, 1×10^2	-	-	-	0, 0	$2x10^3$, $2x10^3$	$2x10^3$, $2x10^3$	Not drained	
12	20.9	0.1	0.5	3×10^3, 1×10^2	-	-	-	0, 0	$2x10^3$, $2x10^3$	$2x10^3$, $2x10^3$	Not drained	Calculation time of 2hr

To be continued

Run No.	Initial oxygen conc.(%)	sodium leakage		Gas leak flowrate from 1-cell, 2-cell to the atmosphere, respectively(m^3/hr)	ventilation flowrate from 1-cell, 2-cell to the atmosphere, respectively(m^3/hr)	exhaust flowrate from 1-cell, 2-cell to the atmosphere respectively(m^3/hr)	N_2 injection flowrate from 1-cell, 2-cell to the atmosphere respectively (m^3/hr)	Gas flowrate from 1-cell, 2-cell to the atmosphere at each differential pressure(kPa), (m^3/hr)			Sodium drain to dump tank	Remark
		rate (kg/h)	duration (hr)					-0.1	3.01	100.1		
13	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	-	-	-	0, 0	2x10^3, 2x10^3	2x10^3, 2x10^3	Drained	
14	20.9	0.1	0.5	3 x 10^3, 1 x 10^2	-	-	-	0, 0	2x10^3, 2x10^3	2x10^3, 2x10^3	Drained	Calculation time of 2hr
15	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	3,840, 9,600	3,840, 9,600	-	0, 0	2x10^3, 2x10^3	2x10^3, 2x10^3	Not drained	
16	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	3,840, 19,200	7,680, 9,600	-	0, 0	2x10^3, 2x10^3	2x10^3, 2x10^3	Not drained	
17	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	3,840, 9,600	7,680, 19,200	-	0, 0	2x10^3, 2x10^3	2x10^3, 2x10^3	Not drained	
18	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	-	3,840, 9,600	3,840, 9,600 during 0.02hr from 0.00775hr	0, 0	2x10^3, 2x10^3	2x10^3, 2x10^3	Not drained	
19	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	-	3,840, 9,600	7,680, 19,200 during 0.02hr from 0.00775hr	0, 0	2x10^3, 2x10^3	2x10^3, 2x10^3	Not drained	
20	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	-	3,840, 9,600	3,840, 9,600 during 0.1hr from 0.00775hr	0, 0	2x10^3, 2x10^3	2x10^3, 2x10^3	Not drained	
21	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	-	15,360, 38,400	15,360, 38,400 during 0.02hr from 0.00775hr	0, 0	2x10^3, 2x10^3	2x10^3, 2x10^3	Not drained	
22	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	-	-	-	0, 0	0, 0	0, 0	Not drained	
23	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	3,8400, 9,6000	3,8400, 9,6000	-	0, 0	0, 0	0, 0	Not drained	
24	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	3,8400, 9,6000 during 0.01hr	3,8400, 9,6000 during 0.01hr	-	0, 0	0, 0	0, 0	Not drained	
25	20.9	10.0	0.5	3 x 10^3, 1 x 10^2	3,840, 9,600 during 0.01hr	3,840, 9,600 during 0.01hr	-	0, 0	0, 0	0, 0	Not drained	

To be continued

Run No.	Initial oxygen conc.(%)	sodium leakage		Gas leak flowrate from 1-cell, 2-cell to the atmosphere, respectively(m^3/hr)	ventilation flowrate from 1-cell, 2-cell to the atmosphere, respectively(m^3/hr)	exhaust flowrate from 1-cell, 2-cell to the atmosphere respectively(m^3/hr)	N_2 injection flowrate from 1-cell, 2-cell to the atmosphere respectively (m^3/hr)	Gas flowrate from 1-cell, 2-cell to the atmosphere at each differential pressure(kPa), (m^3/hr)			Sodium drain to dump tank	Remark
		rate (kg/h)	duration (hr)					-0.1	3.01	100.1		
26	20.9	10.0	0.5	3 x 10^5, 1 x 10^2	3,840, 9,600 during 0.02hr	3,840, 9,600 during 0.02hr	-	0, 0	0, 0	0, 0	Not drained	
27	20.9	10.0	0.5	3 x 10^5, 1 x 10^2	3,840, 9,600 during 0.1hr	3,840, 9,600 during 0.1hr	-	0, 0	0, 0	0, 0	Not drained	
28	20.9	10.0	0.5	3 x 10^5, 1 x 10^2	3,840, 9,600 during 0.02hr	3,840, 9,600 during 0.02hr	3,840, 9,600 after 0.02hr	0, 0	0, 0	0, 0	Not drained	
29	20.9	10.0	0.5	3 x 10^5, 1 x 10^2	3,840, 9,600 during 0.1hr	3,840, 9,600 during 0.1hr	3,840, 9,600 after 0.1hr	0, 0	0, 0	0, 0	Not drained	
30	20.9	10.0	0.5	3 x 10^5, 1 x 10^2	3,840, 9,600 during 0.04hr	3,840, 9,600 during 0.04hr	3,840, 9,600 after 0.04hr	0, 0	0, 0	0, 0	Not drained	
31	20.9	10.0	0.5	3 x 10^5, 1 x 10^2	3,840, 9,600 during 0.04hr	3,840, 9,600 during 0.04hr	3,840, 9,600 after 0.04hr	0, 0	2x10^5, 2x10^3	2x10^5, 2x10^3	Drained	
32	20.9	10.0	0.1	3 x 10^5, 1 x 10^2	3,840, 9,600 during 0.04hr	3,840, 9,600 during 0.04hr	3,840, 9,600 after 0.04hr	0, 0	2x10^5, 2x10^3	2x10^5, 2x10^3	Drained	Calculation time of 0.5hr
33	20.9	10.0	0.1	3 x 10^5, 1 x 10^2	3,840, 9,600 during 0.04hr	3,840, 9,600 during 0.04hr	3,840, 9,600 after 0.04hr	2x10^5, 2x10^5	2x10^5, 2x10^3	2x10^5, 2x10^3	Drained	Calculation time of 0.5hr
34	20.9	10.0	0.1	3 x 10^5, 1 x 10^2	3,840, 9,600 during 0.04hr	3,840, 9,600 during 0.04hr	3,840, 9,600 after 0.04hr	2x10^5, 2x10^5	2x10^5, 2x10^3	2x10^5, 2x10^3	Drained	Gas flow from each cell to the atmosphere at △P of -1.0kPa
35	20.9	10.0	0.5	3 x 10^5, 1 x 10^2	-	-	-	0, 0	0, 0	0, 0	Not drained	heat relaease from the outside wall to the atmososphere
36	20.9	10.0	0.5	3 x 10^5, 1 x 10^2	3,840, 9,600 during 0.04hr	3,840, 9,600 during 0.04hr	3,840, 9,600 after 0.04hr	0, 0	2x10^5, 2x10^3	2x10^5, 2x10^3	Drained	Flow path area of 1.25m^2

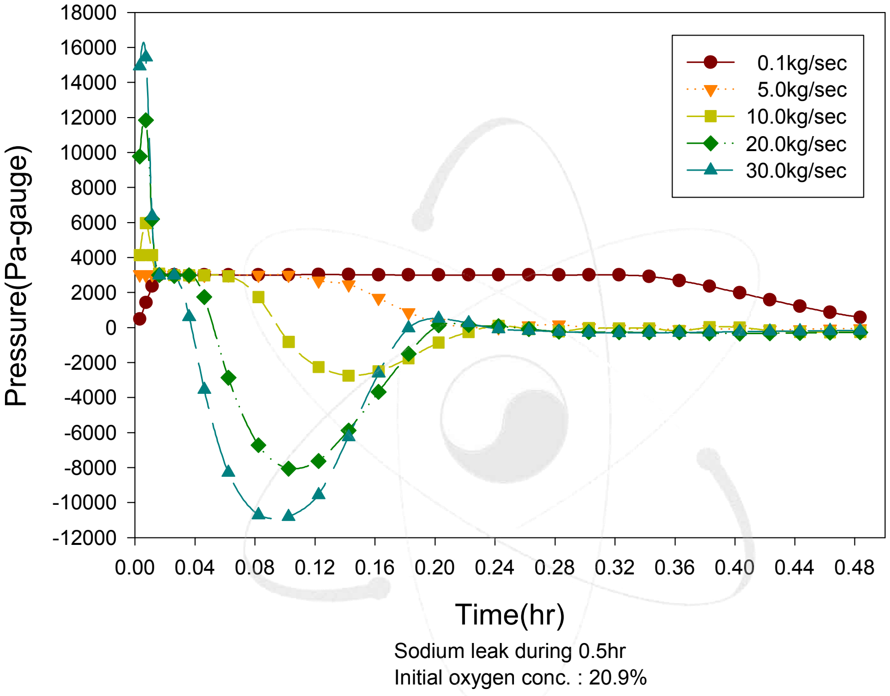


Fig. 7. Effect of sodium leak rate on gas pressure.

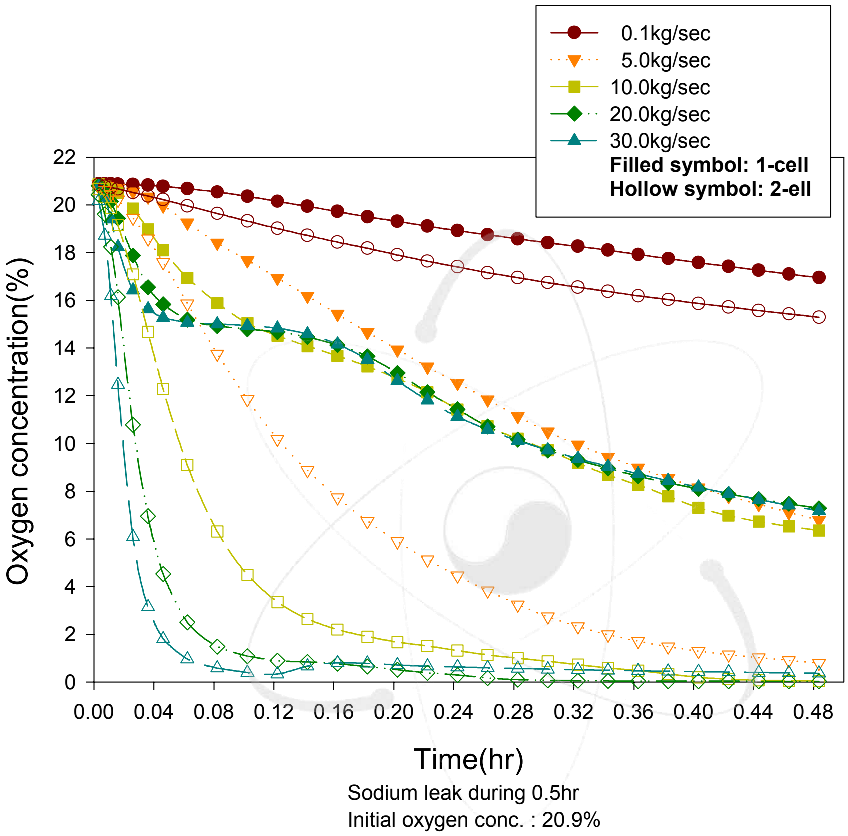


Fig. 8. Effect of sodium leak rate on oxygen concentration of each cell.

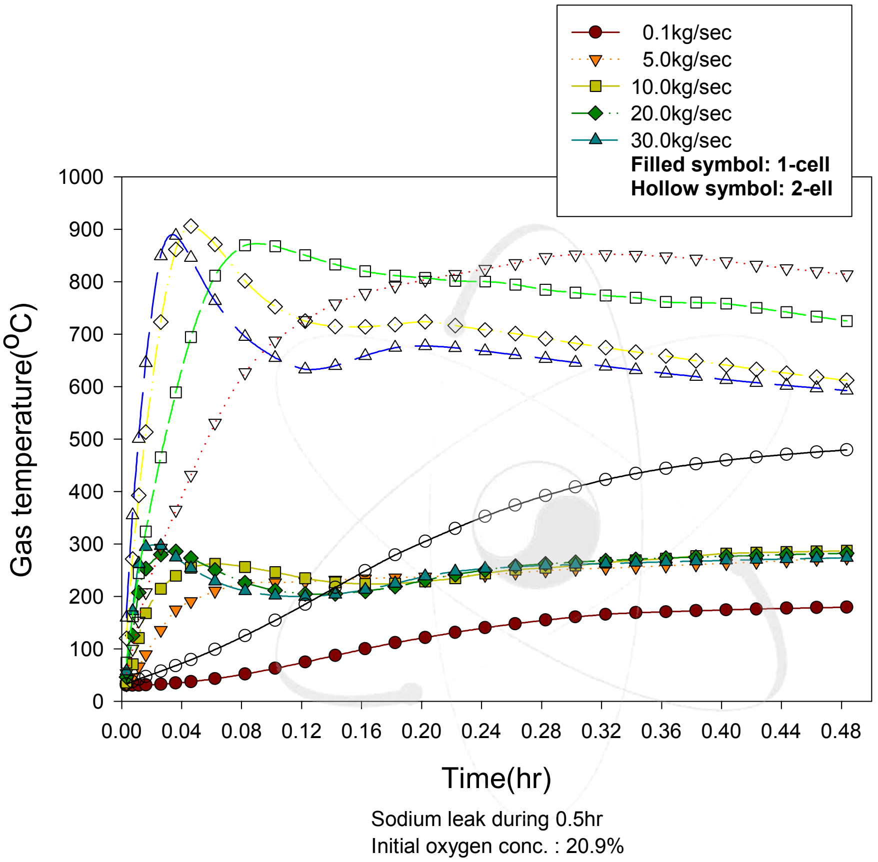


Fig. 9. Effect of sodium leak rate on gas temperature of each cell.

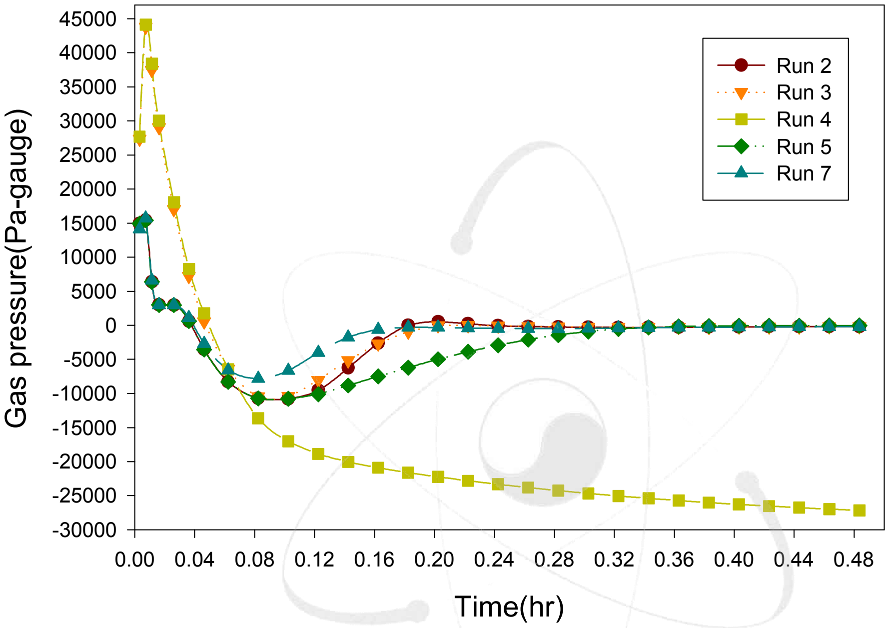
time of 0.094hr when pressure is at a minimum(-10,990Pa). After the pressure reaches the atmospheric pressure, it is kept constant during the computation time of 0.5hr. The trends of the pressure transients at 0.1, 5.0, 10.0, and 20.0 kg/sec appear to be very similar to that at leak rate of 30.0kg/sec. But the increase and the decrease of the pressure up to maximum and minimum respectively is greatly affected by sodium leak rate. It shows that when the leak rate of 0.1kg/sec, the calculated pressure stays below 3,000Pa at which the pressure release plate open. Peak pressure at a rate of 30.0kg/sec is roughly six times as high as that of 5.0kg/sec. This difference in peak pressure is nearly the same as that in leak rate, which the leak rate ratio of 30.0kg/sec to 5.0kg/sec is six times. In the case of all the leak rates, there is the moment which pressures are kept constant at 3,000Pa as shown in figure. This is due to the balance of the heat generated by sodium combustion and the pressure required for opening of pressure release plate which relieves the pressure increase within the cell. The time which pressures are kept constant varies with the leak rates. The pressure release plate is to open if the gas pressure in cell exceeds 3,000Pa. This causes a momentary drop in gas pressure in cell. Also, the rapid decrease of oxygen concentration and the gas leak to the outside lead to a momentary drop in pressure. Fig. 8 shows that transient of oxygen concentration match with that of the pressure. The hollow triangle up symbol shows the change of oxygen concentration at leak rates of 30.0kg/sec in 2-cell which sodium spray fire occurs. 6.4% oxygen of 2-cell is consumed at 0.00529hr when the pressure is maximized. But 83% oxygen is consumed rapidly in the range of 0.0hr to 0.0523hr when the pressure become negative. But at leak rates of 5.0kg/sec, no more than 15% oxygen is consumed gradually at 0.0523hr after the initiation of the leak. The computed gas temperatures at sodium leak rates of 0.1, 5.0, 10.0, 20.0, and 30.0kg/sec are shown in Fig. 9. It is founded that the peak temperatures are 171, 275, 288, 288, and 299℃ for 1-cell, 481, 852, 873, 906, and 890℃ for 2-cell at leak rates of 0.1, 5.0, 10.0, 20.0, and 30.0kg/sec, respectively. The peak temperatures are shown at time later than the peak pressures. As can be seen in figure, when the leak rate is 20.0 and 30.0kg/sec, immediately after the gas temperature in 2-cell reaches rapidly maximum at the beginning of sodium leakage, it decreases somewhat rapidly and again gradually. The gas temperature at rate of 5.0 and 10.0kg/sec increases less rapidly than that at 20.0 and 30.0kg/sec, and then increase gradually all the computation time. However in case that the leak rate is 0.1kg/sec, the gas temperature increases gradually without any decrease of the temperature all the computation time. This is because the oxygen is sufficiently present to maintain sodium combustion within the cell. Almost the same tendency is calculated for 1-cell except that the temperatures of 1-cell are lower than those of 2-cell.

3.2.2 Effect of gas leak, pressure release, sodium leak duration, and sodium drain

Fig. 10, 11, and 12 show the computed results of Run 2, 3, 4, 5, and 7. In the case of Run 2, the pressure release plate is postulated to open at the differential pressure of 3.01kPa with gas flowrate of $2x10^3$, $2x10^5$ m^3/hr, respectively for the 1-cell and the 2-cell. In the contrast with Run 2, Run 3 postulates that the pressure release plate is open at the differential pressure of 100.1kPa with gas flowrate of $2x10^3$, $2x10^5$ m^3/hr, respectively for the 1-cell and the 2-cell. As a result of computation, it is shown that the peak pressure is greatly affected by whether or not the pressure release plate opens. The pressure calculated by Run 3 increases rapidly with the time, up to maximum(43,790Pa in 0.000734hr), which becomes roughly three times as high as that of Run 2. The subsequent pressure changes for Run 2 and Run 3 after 0.0644hr show almost the same tendency due to gas leak between cell and the outside. If there is no gas leak between cell and the outside(Run 4), the pressure increases rapidly, up to a maximum the same as that of Run 3 and then decreases, and is kept negative without any increase of the pressure until the computation time of 0.5hr. It is considered that this is because cell atmosphere is cooled without the subsequent sodium combustion due to 94% oxygen consumption at time of 0.0543hr. Run 5 postulates that sodium leak is terminated after 0.1hr and then the computation is extended to time of 0.5hr. The pressure changes between Run 2 and Run 5 is exactly the same except that the pressure of Run 5 remains rather low than that of Run 2 in the range of 0.1hr to 0.33hr. It is considered that the pressure after 0.1hr is sightly affected by leak duration time because the sodium leak rate of 30kg/sec is sufficiently large to consume 98.1% oxygen within 2-cell in 0.1hr after sodium leakage as shown in Fig.11. And it is seen from the filled diamond symbol of Fig. 11 that the oxygen concentration of Run 5 again increases gradually at time of 0.1hr due to the inflow of the atmospheric gas into 2-cell. It is postulated that the sodium is drained into the dump tank(Run 7). Drain of sodium into dump tank has an slight effect on the pressure and temperature(Fig. 12). This is because the subsequent heat addition rate from pool is less than the heat addition rate from spray and the rate of heat loss from gas. But no significant difference in oxygen concentration changes between Run 2 and Run 7 is made. The temperature for Run 2, 3, 4, 5, and 7 appears to reach a maximum(~898℃) at the same time of 0.0332hr as shown Fig. 12

3.2.3 Effect of air ventilation and N_2 injection

Fig. 13, 14, and 15 show what effects of sodium drain, ventilation and N_2 injection was made on the pressure, oxygen concentration, gas temperature. Run 15 postulates that the air is ventilated into the 1-cell and the 2-cell at rate of 3,840 and $9,600m^3/hr$,



Sodium leak : 30kg/sec
Initial oxygen conc. : 20.9%

Fig. 10. Effect of gas leak, pressure release, sodium leak duration, and sodium drain on gas pressure.

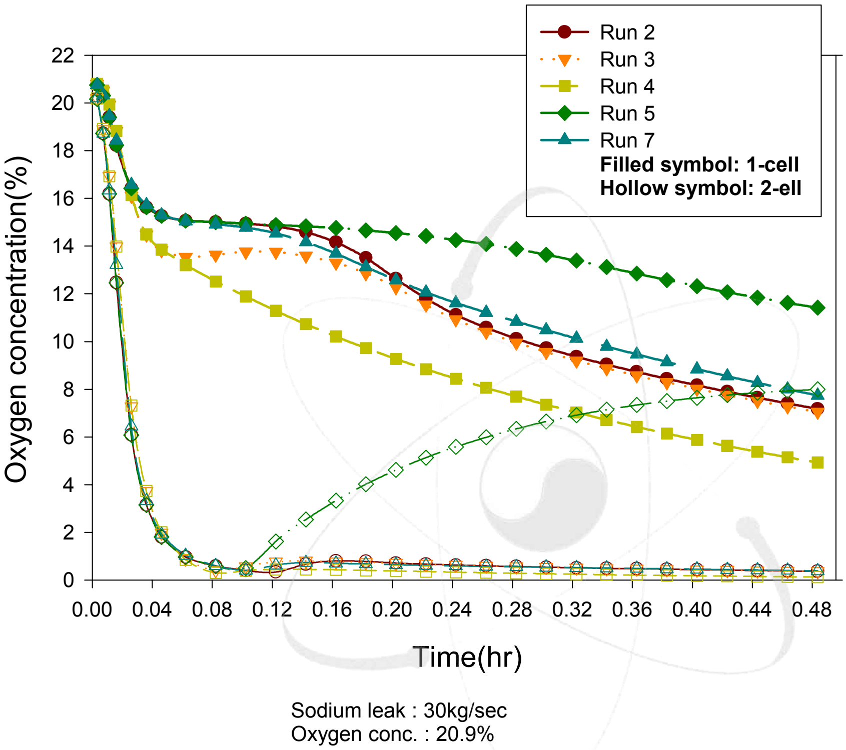


Fig.11. Effect of gas leak, pressure release, sodium leak duration, and sodium drain on oxygen concentration of each cell.

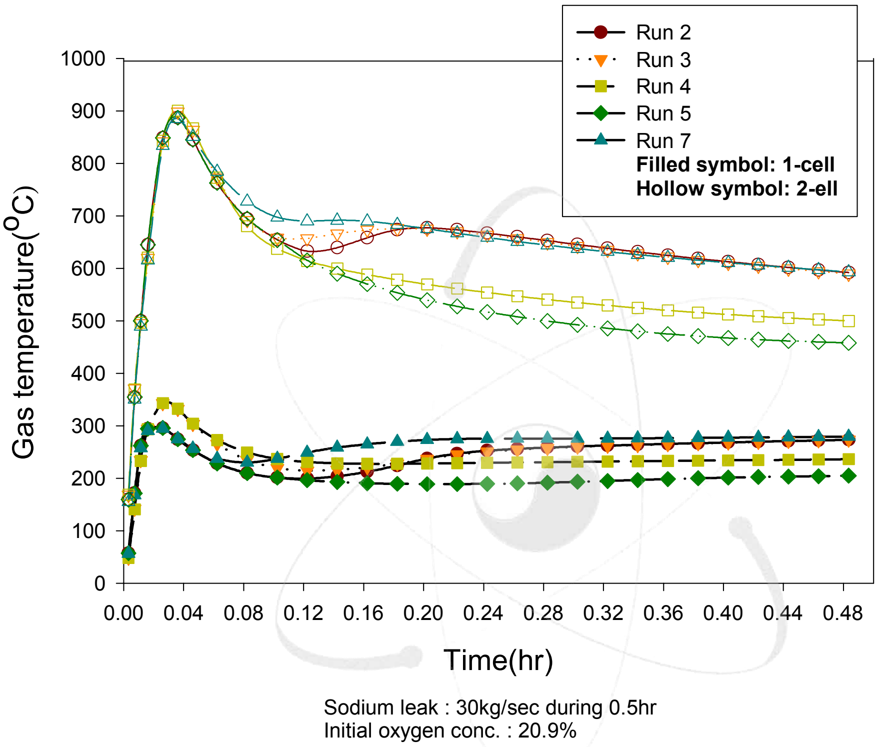
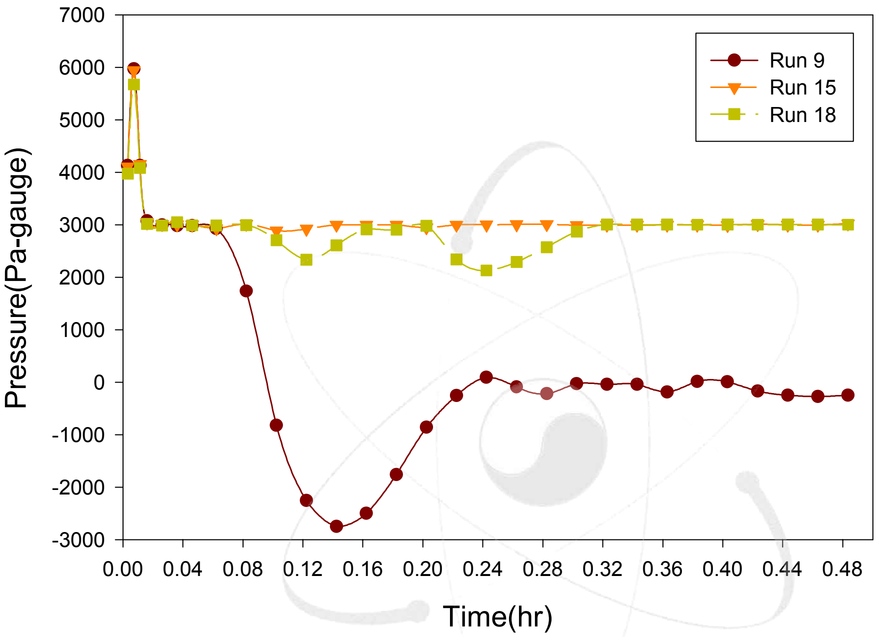
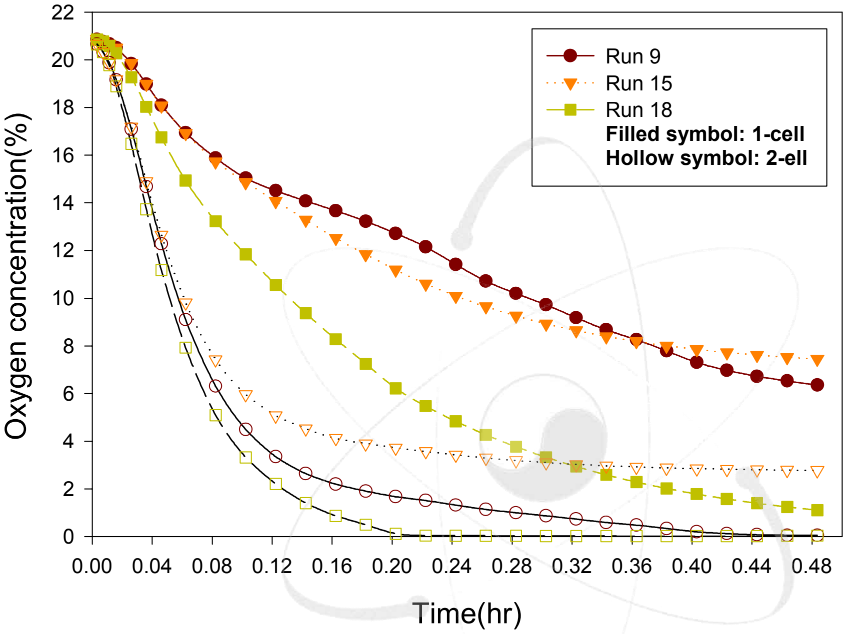


Fig. 12. Effect of gas leak, pressure release, sodium leak duration, and sodium drain on gas temperature of each cell.



Sodium leak : 10kg/sec during 0.5hr
Initial oxygen conc. : 20.9%

Fig. 13. Effect of air ventilation and N_2 injection on the gas pressure.



Sodium leak : 10kg/sec during 0.5hr
Initial oxygen conc. : 20.9%

Fig. 14. Effect of air ventilation and N_2 injection on the oxygen concentration of each cell.

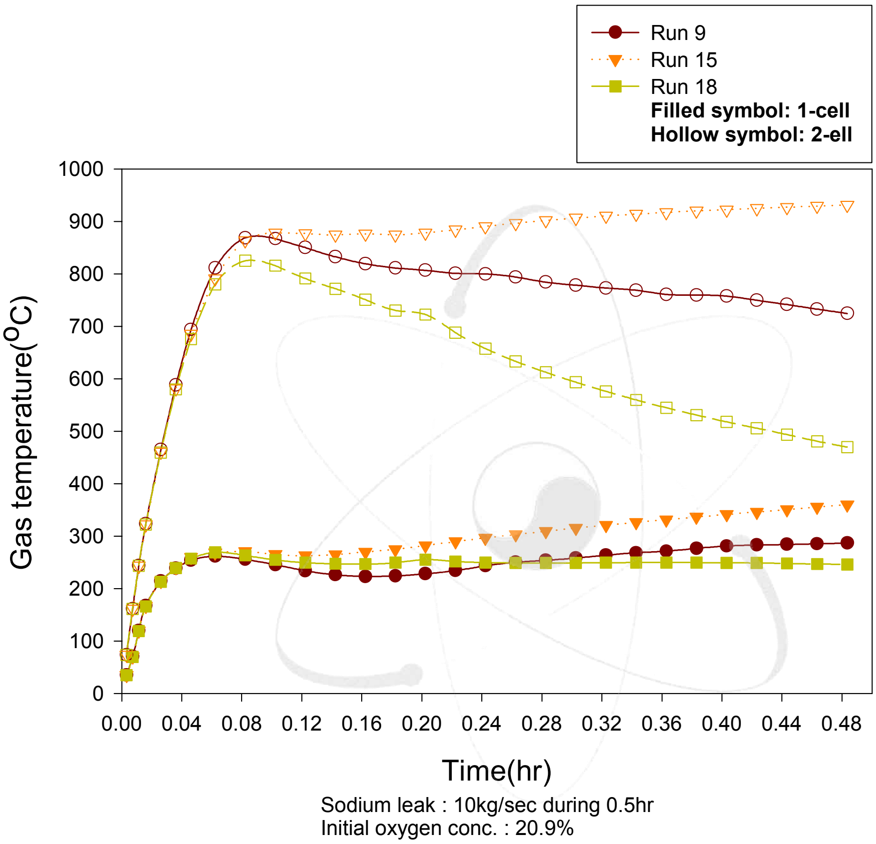


Fig. 15. Effect of air ventilation and N_2 injection on the gas temperature of each cell.

at that same time, the gas within the 1-cell and the 2-cell is exhausted to outside at rate of 3,840 and 9,600m^3/hr. The calculated peak pressure of Run 15 increases rapidly, up to a almost the same maximum(5,938Pa) as that of Run 9 at time of 0.00734hr, which the air ventilation is not considered, and then decreases rapidly. Thereafter it is held constant at 3,000Pa higher than that of Run 9. It can be explained this is because the air flows into cell so that a lot of oxygen is present within each cell as shown in square symbol of Fig. 14. For this reason, after the temperature increases rapidly, and then has a tendency to increase gradually throughout the computation time as shown in square symbol of Fig.15. In case that the air within the cell is replaced by nitrogen into the 1-cell and the 2-cell at rate of 3,840 and 9,600m^3/hr respectively during 0.02hr at the time of 0.0075hr after the initiation of sodium leakage, there is a pressure oscillation as shown from the square symbol in legend due to the inflow of nitrogen into the cell(Run 18). The pressure reaches a maximum(5,669Pa) lower than that of Run 9 and 15, which do not consider the inflow of nitrogen gas into the cell. Also the temperature reaches a maximum(826℃) lower than that of Run, 9 and 15, and then it decreases rather rapidly than that of Run 9 and 15.

The calculated results under each condition of Run 18, 19, 20, 21 are shown in Fig. 16, 17, and 18. It is founded that the momentary inflow of much nitrogen gas into the cell has greater effect on the gas pressure, oxygen concentration, and gas temperature than sodium leak duration time as shown in the figures. The peak pressure(5,046Pa) of Run 21, which postulates the inflow of N_2 injection at rate of 15,360m^3/hr(1-cell) and 38,400m^3/hr(2-cell) during 0.02hr in 0.00775hr after the initiation of sodium leakage, is lower than that(5,669Pa) of Run 18 with the inflow of N_2 injection at rate of 3,840m^3/hr(1-cell) and 9,600m^3/hr(2-cell) during 0.02hr in 0.00775hr after the initiation of sodium leakage. Also the gas temperature and oxygen concentration of Run 21 remains rather low than those of Run 18.

The ventilation conditions, drain system, pressure relief system, and nitrogen injection condition for various fire events are simulated to mitigate and minimize the effect of the sodium fire on the cells after the initiation of sodium leakage as shown in Run 28, 29, 30, 31, 32, 33, and 34 of table 3. Run 34 postulates that nitrogen gas is injected at a rate of 3,840m^3/hr(1-cell), 9,600m^3/hr(2-cell) immediately after ventilation system is shut down to control the sodium combustion at time of 0.04hr after the initiation of sodium leakage. And the pressure release plate opens at the pressure drop of -0.1, 3.01 and 100.1kPa, simultaneously the gas flows from each to the outside at a rate of $2x10^5$m^3/hr to release the pressure of the cell. It is founded that the peak pressure of S/G building with sodium fire mitigation system becomes roughly 39 times as low as that of S/G building without sodium fire mitigation system as shown in Fig.19. Also the gas

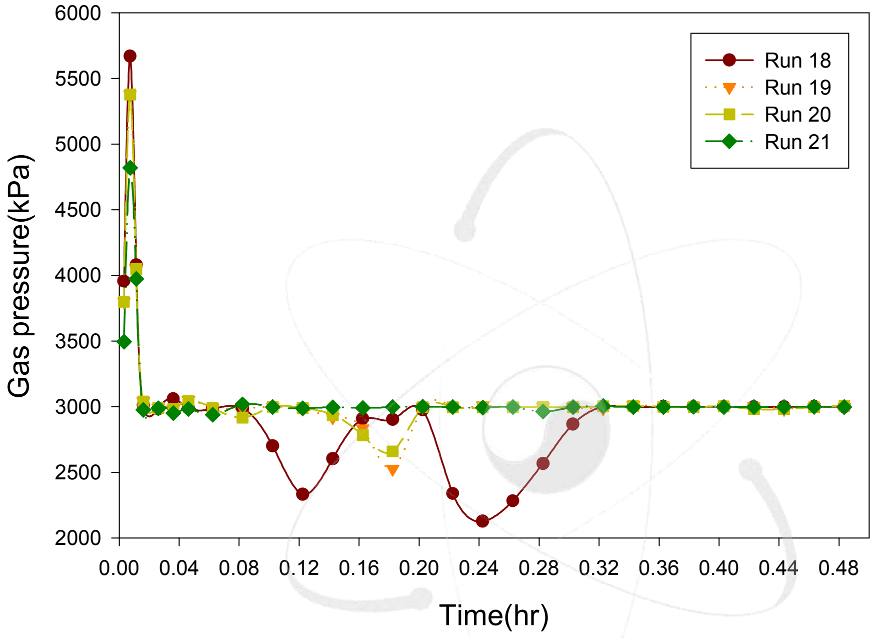


Fig. 16. Effect of N_2 injection condition on gas pressure.

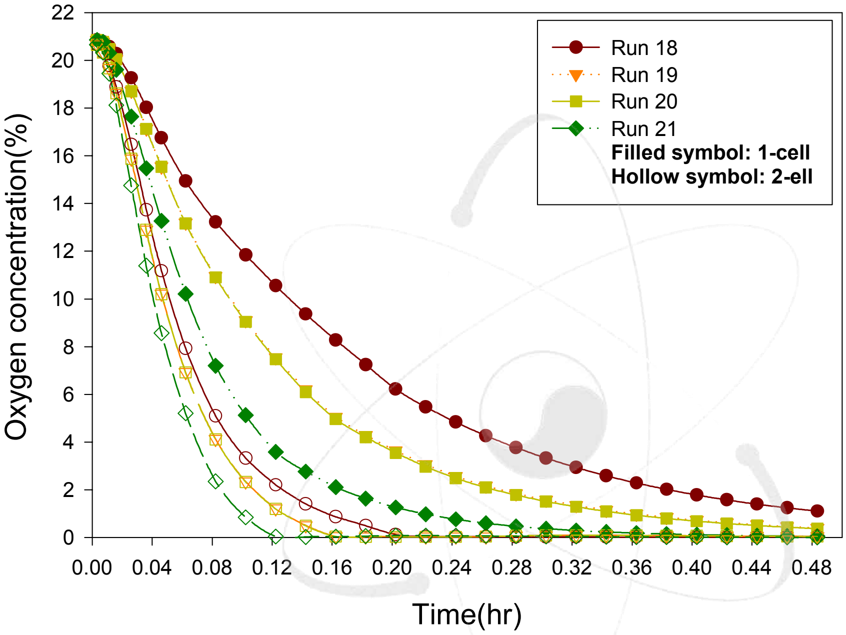


Fig. 17. Effect of N_2 injection condition on the oxygen concentration of each cell.

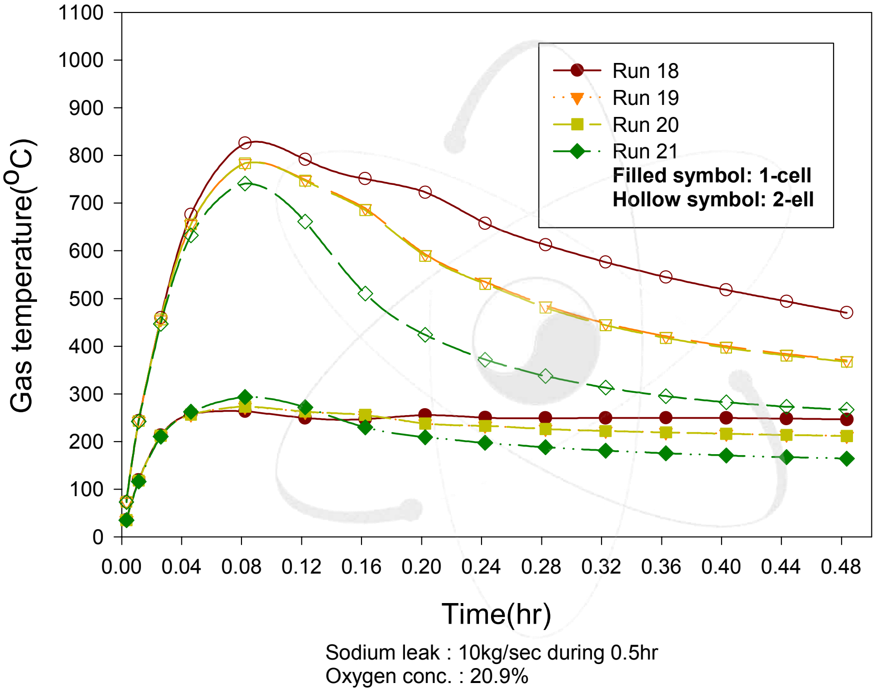
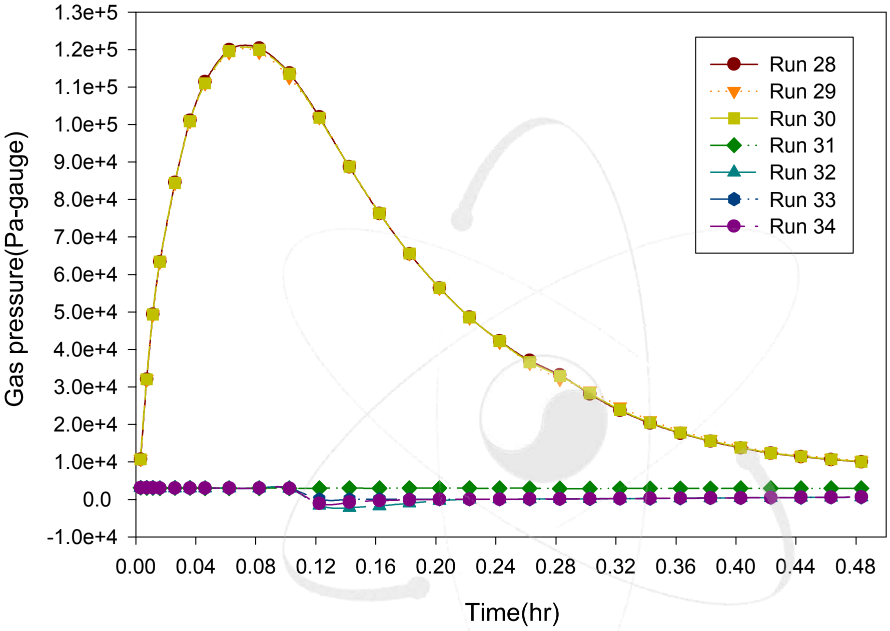


Fig. 18. Effect of N_2 injection condition on the gas temperature of each cell.

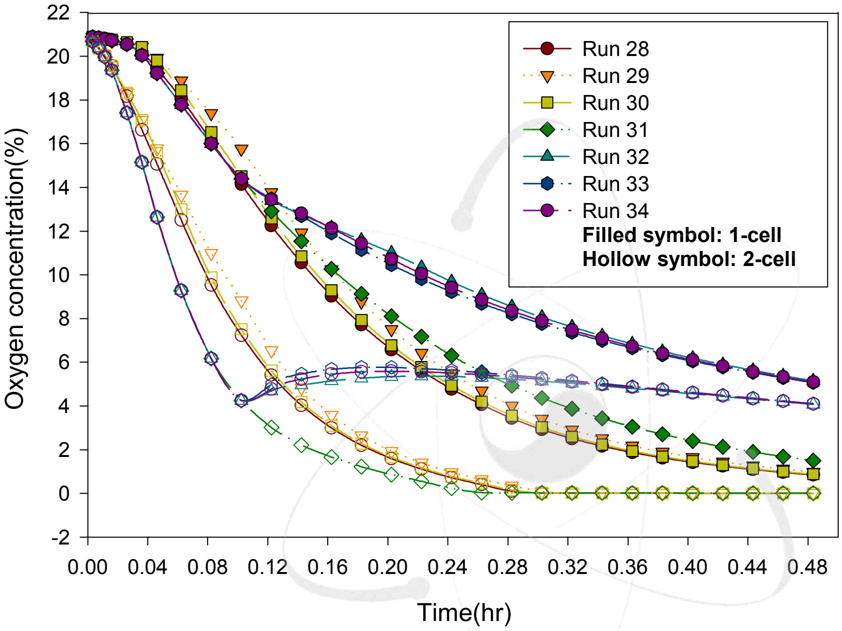


Initial oxygen conc. : 20.9%

Sodium leak rate : 10kg/sec
Initial oxygen conc. : 20.9%
Ventilation and exhaust rate in each cell : 3,840, 9,600m^3/hr
Flow rate of nitrogen gas : 3,840, 9,600m3/hr^3/hr

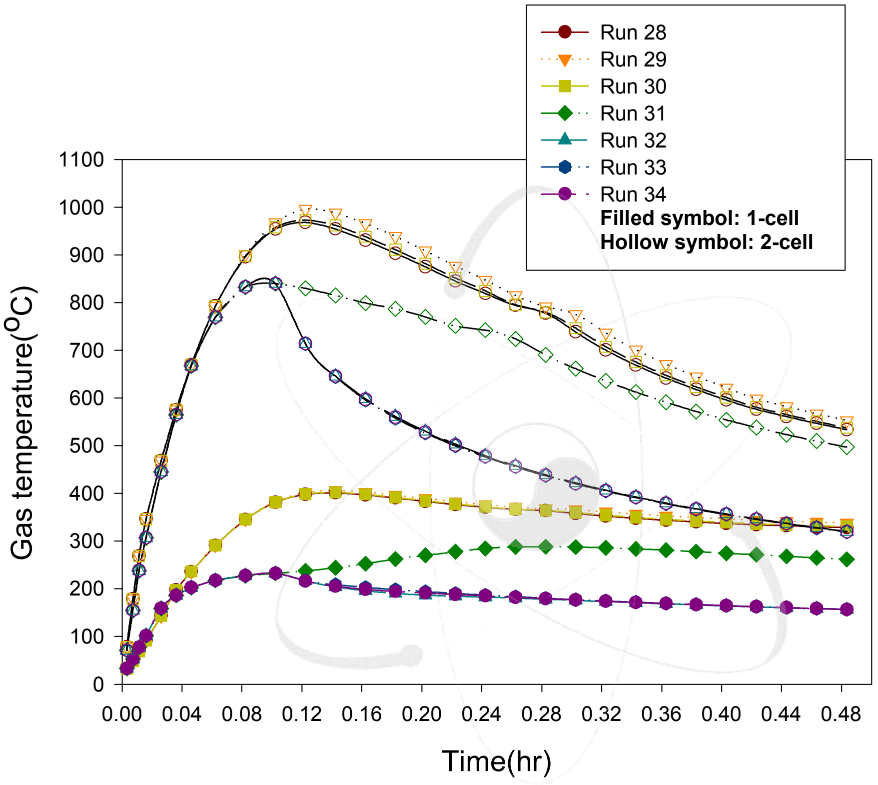
Fig. 19. Effect of ventilation, exhaust, pressure release, sodium leak duration, and sodium drain on gas pressure.

temperature and the oxygen concentration of S/G building with sodium fire mitigation system is kept lower than that of S/G building without sodium fire mitigation system as shown in Fig.20, 21.



Sodium leak rate : 10kg/sec
Initial oxygen conc. : 20.9%
Ventilation and exhaust rate in each cell : 3,840, 9,600m^3/hr
Flow rate of nitrogen gas : 3,840, 9,600m3/hr^3/hr

Fig. 20. Effect of ventilation, exhaust, pressure release, sodium leak duration, and sodium drain on oxygen concentration of each cell.



Sodium leak rate : 10kg/sec
Initial oxygen conc. : 20.9%
Ventilation and exhaust rate in each cell : 3,840, 9,600m^3/hr
Flow rate of nitrogen gas : 3,840, 9,600m3/hr^3/hr

Fig. 21. Effect of ventilation, exhaust, pressure release, sodium leak duration, and sodium drain on gas temperature of each cell.

4. Conclusions

From the calculated results the following conclusions can be drawn;

(1) The peak pressures become higher as the sodium leak rate increases, and the leak rate has significant effect on gas pressure in cell. The peak pressure at a rate of 30.0kg/sec is roughly six times as high as that of 5.0kg/sec. This difference in peak pressure is nearly the same as that in leak rate, which the leak rate ratio of 30.0kg/sec to 5.0kg/sec is six times.

(2) The peak pressure is greatly affected by whether or not the pressure release plate opens. The calculated pressure of the cell with the pressure release plate increases rapidly with the time, up to maximum, which becomes roughly three times as high as that of the cell without the pressure release plate.

(3) Drain of sodium into dump tank has an slight effect on the pressure and temperature because the subsequent heat addition rate from pool is less than the heat addition rate from spray and the rate of heat loss from gas.

(4) The quick shutdown of ventilation system and the injection of nitrogen gas are very effective against the sodium leakage and fire accidents. The peak pressure of S/G building with sodium fire mitigation system becomes roughly 39 times as low as that of S/G building without sodium fire mitigation system. Also the gas temperature and the oxygen concentration of S/G building with sodium fire mitigation system is kept lower than that of S/G building without sodium fire mitigation system.

서지정보양식

수행기관보고서번호		위탁기관보고서번호		표준보고서번호	INIS 주제코드
KAERI/TR-					
제목/부제	소듐누출로 인한 소듐 연소 현상 분석				
연구책임자 및 부서명 (AR/TR 등의 경우 주저자)	김병호				
연구자 및 부서명	정지영, 정경채, 김태준, 최종현(칼리머기술개발팀)				
출 판 지	대전	발행기관	한국원자력연구소	발행년	2001. 12.
페 이 지	60P	도 표	있음(∨), 없음( )	크 기	A4
참고사항					
비밀여부	공개(∨), 대외비( ), __ 급비밀		보고서종류	기술보고서	
연구위탁기관			계약 번호		

초 록

고속증식로의 화전안전대책을 마련하기 위하여 소듐화재로 인한 에어로졸의 방출, 빌딩내에서의 온도 및 압력의 상승을 고려하는 것이 중요하다. 이러한 이유 때문에 다양한 소듐누출에 기인한 소듐화재의 특성을 파악할 필요가 있다. ASSCOPS(Analysis of Simultaneous Sodium Combustion in Pool and Spray)는 고속증식로에서 소듐 누출 및 화재사고를 분석하기 위하여 Japan Nuclear Cycle Development Institute(JNC)에 의하여 개발된 코드이다. 본 연구에서는 ASSCOPS code를 사용하여 KALIMER(Korea Advanced Liquid Metal Reactor)의 증기발생기에서의 소듐 누출 및 화재사고에 대한 예비분석을 수행하였다. 분무형 및 풀형 소듐 연소현상, 건물내에서의 압력 및 온도변화, 구조재의 온도변화, 에어로졸 거동, 안전밸브를 갖춘 건물에서의 환기 특성, 불활성기체의 유입에 따른 화재영향 등이 평가되었다. 계산결과, 소듐화재 발생후 소듐누출이 파이프 시스템으로부터 얼마나 지속되는가에 따라서, 환기시스템의 가동 여부, 불활성 기체의 유입 여부 및 시점, 누출된 소듐의 drain 여부, 그리고 건물의 외부로부터의 격리 여부에 따라서 차후 화재영향이 다양하게 나타났다. 특히, 각 건물의 벽면에 압력개방판을 설치함으로써 과도한 압력 상승을 미연에 방지 할 수 있었다.

주제명 키워드	소듐화재 현상 분석, 소듐 누출, 소듐 화재 완화시스템

BIBLIOGRAPHIC INFORMATION SHEET

Performing Org. Report No.	Sponsoring Org. Report No.	Standard Report No.	INIS Subject Code
KAERI/TS-			

Title / Subtitle	Analytical study of sodium combustion phenomena under sodium leak accidents
Project Manager and Department (or Main Author)	Kim Byung-Ho
Researvher and Department	Jeong J.Y., Jeong K.C., Kim T.J., Choi.J.H.

Pub. Place	Taejon	Publisher	KAERI	Pub. Date	2001. 12
Page	60P	Ill. & Tab.	Yes(∨), No ( )	Size	A4
Note					

Classified	Open(∨),Restricted( ),Class Document	Report Type	TR
Sponsoring Org.		Contract No.	

Abstract

The rise of temperature and pressure, the release of aerosol in the buildings as a result of sodium fire must be considered for the safety measures of LMR. Therefore for the safety of the LMR, it is necessary to understand the characteristics of sodium fire, resulting from the various type of leakage. ASSCOPS(Analysis of Simultaneous Sodium Combustion in Pool and Spray) is the computer code for the analysis of the thermal consequence of sodium leak and fire in LMR that has been developed by Japan Nuclear Cycle Development Institute(JNC) in Japan. In this study, a preliminary analysis of sodium leak and fire accidents in S/G building of KALIMER is made by using ASSCOPS code. Various phenomena of interest are spray and pool burning, peak pressure, temperature change, local structure temperature, aerosol behavior, drain system into smothering tank, ventilation characteristics at each cell with the safety venting system and nitrogen injection system.

In this calculation, the dimension of the S/G building was chosen in accordance with the selected options of LMR name KALIMER(Korea).

As a result of this study, it was shown that subsequent effect of sodium fire depended upon whether the sodium continued to leak from the pipe or not, whether the ventilation system was running, whether the inert gas injection system was provided, whether the sodium on floor was drained into the smothering tank or not, whether the building was sealed or not, etc. Specially the excessive rise of pressure into each cell was prevented by installing the pressure release plates on wall of the building.

Subject Key-words	Sodium fire phenomena, Sodium leak, Mitigation system