# ENERGY RELEASE FROM
# SODIUM SPRAY COMBUSTION

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ABSTRACT

Energy release associated with sodium spray combustion was determined and a computer code was developed to analyze combustion of sodium particles in the atmosphere depleted of oxygen.

Liquid sodium heated at 300 ~ 500 $^{\circ}$C was injected as much as 400 gr into a closed vessel of 2 m$^3$. Atmosphere in the vessel was controlled by mixing nitrogen gas with dry air and wet air 0 ~ 21 % in oxygen concentration and 0 ~ 75 % in humidity. Temperatures and pressure of the atmosphere were recorded to observe their rises and drops with time during and after sodium injection. Peak pressure rose with increases in oxygen concentration and temperature of injected sodium, being more sensitive to the concentration than the temperature. The peak pressure did not reach a level which was obtained from theoretical energy release from sodium

spray combustion because of incomplete combustion and heat transfer to the vessel wall.

It was assumed in the computer code that heat and mass transfer was controlled respectively by heat conduction and mass diffusion inside a reaction zone and the transfer was governed by convection outside the reaction zone. Calculation results revealed that combustion rate per unit area on the sodium particle was in proportion to oxygen concentration in the ambient gas but in reverse to the particle sizes, and that decreasing rate of square of particle sizes was about 7 x 10$^{-4}$ cm$^2$/s, being smaller in one order of the value of fuel oils.

Change in the pressure obtained from the calculation was on the whole in agreement with that observed in the experiment.

## 1. Introduction

Sodium in the primary cooling system of Fast Breeder Reactors contains the radioactive sodium and corrosion products in the course of normal reactor operations and further fission products when any failure of the fuel cladding. In the hazard analysis of the RBRs, therefore, a significant release of energy and radioactivity is postulated to occur from a sodium fire following the sodium leakage from the system boundaries.

Studies of sodium combustion are undertaken at Hitachi Ltd., sponsored by the Power Reactor and Nuclear Fuel Development Corp., to obtain informations characterizing sodium fires and to design engineering safeguards against consequences to the sodium fires. After reviewing reported investigations[1], we directed our efforts to the studies of energy release associated with sodium spray combustion and of iodine release associated with sodium pool combustion.

Release of sodium spray into an enclosed vessel has been believed to produce rapid increases in pressure and temperature of the ambient gas due to sensible heat exchange and combustion heat release. It has been also considered that the pressure reaches its peak in a short period with limited heat transfer to the vessel wall. However, the peak pressure observed in experiments was reported to be below that calculated with use of ideal assumptions[2]~[7]. Sodium spray combustion will be affected by such parameters as, sodium temperature, oxygen concentration and humidity in the ambient gas, and sizes and motion of sodium particles. Thus, more experimental data are required to understand the complicated roles of these parameters on the sodium spray combustion. Computer codes were developed to describe heat and mass transfer in the combustion process and subsequent pressure-temperature transients[7],[8]. Studies are needed to improve the combustion models of a single sodium particle

and sprayed sodium by comparing calculated results with observed ones. This paper concerns current experimental and analytical works of sodium spray combustion.

2. Experiment of Sodium Spray Combustion

2.1 Experimental

Figure 1 represents an arrangement used in the experiments of energy release associated with sodium spray combustion. The experimental arrangement consists of combustion vessel, a sodium system to spray sodium into the vessel from its bottom, a gas system to control concentrations of oxygen and moisture in the atmosphere, and a monitoring system of temperatures, pressure, and concentrations of oxygen, moisture and aerosol during sodium combustion.

(1) Combustion Vessel

The combustion vessel is a vertical pressure vessel made of carbon steel, 1 m in diameter and 2.8 m high, with a volume of about 2 $m^3$. A spray nozzle installed on the bottom of the vessel injects sodium in an upward cone with a angle of 60 $^\circ$, as illustrated by dotted lines in Fig. 1. Thermocouples are fixed at various locations in the vessel to transmit change in temperatures of the gas atmosphere during and after the sodium combustion. The thermocouples are led out of the vessel through a flange

with glass-to-metal seals. Pressure transmitters are fixed at the top of the vessel to indicate change in gas pressure with time. A rupture disk connected to the vessel releases pressure rise in excess. Aerosol samplers are provided at a lower part of the vessel to inhale the gas containing sodium aerosol.

(2) Sodium Spraying System

The sodium spraying system consists of a tank for supplying sodium to the system, a tank for measuring sodium to be sprayed, a cylinder for pressurizing the sodium by an oil-drived piston, the spray nozzle and pneumatic valves. Sodium transfered into the measure tank by pressurizing cover gas in the supply tank is loaded by suction in the evacuated cylinder after measuring 400 gr by a level gauge. The sodium heated up at 300 ~ 530 $^{\circ}$C and pressurized at 10 kg/cm$^2$ in the cylinder is injected through the spray nozzle into the vessel by opening the pneumatic valve between the cylinder and the spray nozzle. The rate and the amount of injected sodium are determined from records of movement of the piston and opening time of the valve.

Particle distribution of several spray nozzles was tested by varying pressure and flow rate of water to select a nozzle suitable for sodium spray. The selected nozzle has a 2.2 mm throat and an inner guide with spiral grooves on the periphery and a center hole. These spiral grooves and center hole permit the nozzle to spray sodium uniformly in the radial direction.

(3) Gas Controlling System

The gas system functions for controlling gas composition in the vessel, mixing the gas by circulating a part of gas through a loop, and covering sodium free surfaces in the tanks. Oxygen concentration in the gas is controlled by mixing dry air with nitrogen gas and humidity by mixing the gas with wet air. The gas loop is composed of a particle filter, an oxygen meter, a circulating pump, a flow control valve and a flow meter. Argon gas pipings are provided for purging remained sodium from the spray nozzle as well as for covering the sodium free surfaces. The gas in the vessel is replaced with carbon dioxide gas after combustion of sprayed sodium to change combustion products into sodium carbonate.

(4) Monitoring System

Thermocouples used in the experiment are chromel-alumel wires insulated with magnesia and sheathed with stainless steel, 1.6 mm in diameter. They are located at 220, 400, 580, 780 mm above the spray nozzle, 0, 100, 200, 300, 400 mm apart from the axis of the vessel.

Pressure transmitters are of strain gauge type capable of responsing to quick pressure changes. For covering wide change in pressure, one of the transmitters ranges 0 ~ 2 kg/cm$^2$g and another 0 ~ 10 kg/cm$^2$g.

Oxygen concentration in the gas sampled at a rate of 500 cc/min is measured by the oxygen meter of electro-

chemical type. Humidity in the gas is also determined by a meter of dew point type.

The rate and amount of spraying sodium are obtained from relation between an amount of injected sodium and stroke of the piston, which is converted into voltage.

Aerosol concentration in the gas is obtained as reference data of the energy release experiment. The gas containing aerosol of sodium oxide are taken into the evacuated samplers at 1, 10, 100 min after spraying sodium. Sodium aerosol taken into the samplers is dissolved in pure water and determined by atomic adsorption spectrometry.

(5) Preconditioning of Gas and Sodium

The combustion vessel was evacuated below 1 Torr to remove oxygen gas and moisture, and filled with dry air to a partial pressure, equivalent to a ratio of given oxygen concentration to that in air. Then, nitrogen gas was added to the gas till the pressure reached atmospheric pressure. The value of oxygen concentration was confirmed by the oxygen meter. Humidity was likewise conditioned by adding wet air whose absolute humidity was known to dry air whose partial pressure was set up at a given value. The combustion vessel and the gas loop were so warmed that moisture in the gas did not condense on the inner walls.

Sodium in the sodium tank was kept heating at 150 ~ 160 °C prior to loading the sodium in the measure tank by pressurizing cover gas in the supply tank. The cylinder and the piping to the pneumatic valve were evacuated below 1 Torr so as to fill them with the sodium, and heated to a given temperature.

(6) Sodium Spraying

Adjustment was made to the monitoring system before the oil-drived and pneumatic mechanisms were actuated. By pressurizing the cylinder and successively opening the valve, the heated sodium was injected into the combustion vessel. The valve was shut when the piston had moved to a predetermined position. Sudden increases in the temperatures and the gas pressure indicated occurrence of sodium combustion. Decrease in oxygen concentration observed at intervals of several minutes also showed the occurrence.

Sodium remained in the measure tank, and the cylinder was dropped in the supply tank, and sodium in the spray nozzle was purged by flowing argon gas into the vessel.

(7) Vessel Cleaning

The gas in the combustion vessel was exhausted and replaced with room air so that deposited sodium on the inner surface of the vessel became sodium oxide. After repeating this process two or three times, the air was replaced with carbon dioxide gas so as to change the

sodium oxide into sodium carbonate or sodium bicabonate. Powder of sodium carbonates was removed by using a vacuum cleaner.

## 2.2 Results and Discussion

### (1) Particle Size Distribution of Sprayed Sodium

Prior to the combustion experiment, particle sizes of sprayed sodium were determined by using the selected nozzle in the combustion vessel. Sodium heated at about 500 °C and pressurized at the working pressure was sprayed downwards in nitrogen gas atmosphere. Sodium particles passing through a window during opening time of a shutter were collected on a glass plate placed about 150 mm below the nozzle and 70 mm apart from the center line of the spray cone. The collected particles were coated with kerosene within the vessel to prevent them from oxidation and analyzed by their microscopic photograph.

Relation between the cumulative number percent of the collected particles and their sizes are plotted on a log-probability graph in Fig. 2. The linear relation observed in Fig. 2 shows that the sodium particles make a pattern of log-normal distribution. Median diameter read from Fig. 2 is 55 $\mu$ and that weighted by the diameter, surface and volume respectively becomes about 80, 300 and 670 $\mu$, which are considerably greater than reported values [9]～[11] in pool combustion of sodium. This distribution pattern agrees well with that of water determined by using the same nozzle [12] as lons as Weber number is equal to each other, whose value is 1,750 in this case.

### (2) Transients of Temperature and Pressure

Figure 3 shows changes in gas temperature and gas pressure with time measured after spraying sodium, and initial oxygen concentration in the atmosphere. The gas temperature at 220 mm above the spray nozzle indicates the highest value among ones at other points, increasing to 900 °C at the maximum in the case of 21 % oxygen concentration and decreasing gradually after the end of spray. The maximum temperature falls significantly as the oxygen concentration lowers.

Gas temperature in the ending stage of combustion decreases sharply to a level of 200 °C as the position becomes high along the center line of spray cone. Gas temperature is higher at 100 ～ 200 mm apart from the center line of spray cone than that on the center line.

The gas pressure in the vessel increases linearly with time in the initial stage and slowly in the next, reaching a peak before the end of spray, and afterwards decreases with time. This peak pressure is far below a level calculated with use of ideal assumptions, namely, complete combustion of sprayed sodium without heat transfer to the vessel. The peak of the gas pressure falls also sensitively to the lowering in the oxygen concentration.

(3) Change in Peak Pressure

Since the peak pressur is an important data for design of the reactor containment, experimental results were rearranged in Fig. 4 to reveal dependency of the peak pressure on oxygen concentration and initial temperature of sprayed sodium. The peak pressure increases with the increase in the oxygen concentration and keeping of the sodium temperature at elevated levels. Steep and mild increases in the peak pressure are observed when the temperature is kept at 500 $^\circ$C. Since the gas in the vessel is depleted of oxygen below 5 % for complete combustion of 400 gr sodium, the steep increase is attributable to incomplete combustion of sprayed sodium, and thus the mild one to enhancement of combustion rate with rising temperature. A steady increase is observed in the peak pressure with the increase in the sodium temperature when oxygen concentration is nealy equivalent to the combustion of 400 gr sodium, and a slight increase when the combustion takes place in the atmosphere rich in oxygen. A comparison between both effects shown in Fig. 4 reveals that the increase in the oxygen concentration is more sensitive to the increase in the peak pressure than that in the initial temperature of sprayed sodium.

Little difference was observed between the pressure rise associated with the combustion of 530 $^\circ$C sodium in dry air and that in humid air, whose relative humidity was 76 %. An attempt was made to observe an effect of amounts of sprayed sodium on the peak pressure by using another spray nozzle with a throat 3.3 mm in diameter. However, values of the peak pressure divided by amounts of sprayed sodium indicated no significant difference between the uses of both spray nozzles.

(4) Account of Combustion Heat

Assumptions used in the estimation of pressure rises are analyzed to account for the release and transfer of energy associated with combustion of sprayed sodium. Oxygen consumptions are obtained from oxygen concentrations before and in a steady state after the combustion. Spraying sodium in the gas atmosphere containing oxygen will possibly form sodium oxide and sodium peroxide through combustion[13], but their production ratios have not been determined. Then, if it is postulated that sprayed sodium reacts with oxygen present in the gas to form sodium oxide, a combustion ratio can be defined by oxygen consumption observed upon that expected in the complete combustion. The combustion ratio plotted in Fig. 5 indicates a linear increase below 5 ~ 6 % oxygen concentration and a stay around 80 % even in the higher oxygen concentration.

If energy released from the combustion contributed actually to the pressure rise of the gas, its linear increase in the initial stage would continue to a certain level, as illustrated in Fig. 6. The hypothetical peak

pressure can be obtained by extrapolating the linear increase until the end of spray.

Figure 7 represents an account of combustion heat of sprayed sodium as a function of oxygen concentration. The peak pressure marked by a dot-dash-line is obtained from calculation with use of ideal assumptions, namely, combustion of sprayed sodium without heat transfer to the vessel. This ideal peak pressure is lowred to the intermediate curve depicted by a broken line due to incomplete combustion, which is evaluated by the combustion ratio in Fig. 5. Experimental results, which are linked by a solid line, are raised to the top of arrows by extrapolation illustrated in Fig. 6. These extrapolated peak pressures are observed to approach the corrected value. This accounts for the large difference between results obtained from the calculation and the experiment to originate in incomplete combustion of sprayed sodium and transfer of combustion heat to the vessel wall. The combustion rate of sodium particles and the pressure rise due to their combustion are under further analyses.

## 3. Analysis of Sodium Spray Combustion

### 3.1 Analysis

Combustion rates of a single sodium particle will be controlled by processes such as evaporation and diffusion of sodium from the particle, arrival of oxygen gas in the ambient gas to the reaction zone, and transfer of combustion heat to the particle for the evaporation and to the ambient gas. Among sprayed sodium, some smaller size particles will burn out even in the atmosphere depleted of oxygen, but larger size ones will remain not to burn after depositing on the vessel wall and falling on the vessel bottom.

(1) Model of Sodium Particle Combustion

A physical model used in the analysis is represented in Fig. 8 to illustrate the above-mentioned processes. It is assumed in this model that combustion of the sodium particle takes place in the spherical form and in the quasi-steady state and that there is a reaction zone, namely flame, just outside the sodium particle. It is postulated that transfer of combustion heat from the flame to the particle is controlled by heat conduction and radiation and that of sodium vapor from the particle to the flame by diffusion, and that transfers of combustion heat and combustion products into the ambient gas flow are governed by convection as well as arrival of oxygen gas to the flame, and further that the sodium vapor reacts with oxygen gas at an infinitely rapid rate.

(2) Heat and Mass Transfer inside the Flame

On the basis of sodium vapor with density $\rho_s$ and velocity $v_s$, mass flux of sodium vapor from the sodium particle to the flame can be expressed in the form

$$\frac{d}{dr} r^2 [\rho_s \mathcal{V}_s] = \frac{d}{dr} r^2 [\rho_s \mathcal{V}_s Y_s - \rho_s D_s \frac{dY_s}{dr}] = 0 , \qquad (1)$$

where $Y$ and $D$ are respectively mole fraction and diffusion coefficient, and the suffix $S$ denotes sodium. The velocity $\mathcal{V}_s$ is related to combustion rate of the particle $W_s$ by the equation

$$W_s = 4\pi r^2 \rho_s \mathcal{V}_s . \qquad (2)$$

With using a variable

$$\xi = \frac{W_s}{4\pi r \rho_s D_s} , \qquad (3)$$

the right side of Eq. (1) becomes a simple form as

$$\frac{d^2}{d\xi^2} Y_s + \frac{d}{d\xi} Y_s = 0 . \qquad (4)$$

The solution of this equation is

$$Y_s = A_1 + A_2 e^{-\xi} , \qquad (5)$$

where $A_1$ and $A_2$ are constants to be determined by boundary conditions.

Heat transfer by conduction from the flame to the sodium particle can be written in the expression

$$\frac{d}{dr} r^2 \rho_s \mathcal{V}_s C_{ps} T - \frac{d}{dr} r^2 k \frac{dT}{dr} = 0 , \qquad (6)$$

where $C_p$ is specific heat, $T$ temperature and $k$ thermal conductivity. By using another variable as

$$\eta = \frac{W_s C_{ps}}{4\pi r k} , \qquad (7)$$

Eq. (6) is rewritten in the well-known form similar to Eq. (4) and the solution leads to

$$T = B_1 + B_2 e^{-\eta} , \qquad (8)$$

where $B_1$ and $B_2$ are constants to be determined by boumdary conditions. Heat transfer by radiation can be expressed by

$$q_r = 4\pi r_\ell^2 \, \varepsilon_1 \, \sigma_s \, (T_f^4 - T_\ell^4) , \qquad (9)$$

where $\sigma_s$ is Stefan-Boltzman's constant and $\varepsilon_1$ emissivity, and the suffix $\ell$ and $f$ denote respectively the liquid sodium particle and the flame.

(3) Heat and Mass Transfer outside the Flame

Mass transfer by forced convection around a sphere can be described by the Sherwood equation as a function of Reynolds number and Schmidt number[14]

$$Sh = 2 + 0.6 \, Re^{\frac{1}{2}} \, Sc^{\frac{1}{3}} . \qquad (10)$$

Oxygen flux arriving in the flame $W_0$ is obtained from the relation

$$\frac{W_0}{M_0} = 2\pi r_f \cdot Sh \, D_0 \cdot N_0 \, Y_0 , \qquad (11)$$

where $N_0$ and $M_0$ are respectively molar concentration and molecular weight and the suffix $0$ denotes oxygen. A part of heat generated at the flame is transferred into the ambient gas similarly in accordance with the Nusselt correlation,[15] a function of Reynolds number and Prandtl number,

$$Nu = 2 + 0.6 \, Re^{\frac{1}{2}} \, Pr^{\frac{1}{3}} . \qquad (12)$$

Thus, heat flux by the forced convection becomes

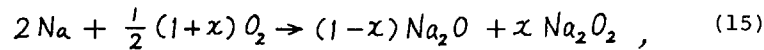$$Q_c = 2\pi r_f \cdot Nu \, k \cdot (T_f - T_g) , \qquad (13)$$

and that by radiation into the ambient gas leads to

$$Q_r = 4\pi r_f^2 \cdot \varepsilon_2 \, \sigma_s \, (T_f^4 - T_g^4) , \qquad (14)$$

where $\varepsilon_2$ is emissivity and the suffix $g$ indicates the ambient gas.

(4)  Heat Flux and Mass Flux at the Flame

Since reaction of sodium with oxygen can be expressed in the form with production ratio of sodium peroxide $x$

$$2 Na + \frac{1}{2}(1+x) O_2 \rightarrow (1-x) Na_2O + x Na_2O_2 ,\qquad(15)$$

the mass flux becomes proportional to molecular weight in chemical equivalent as shown by the equation

$$\frac{W_s}{M_s} = \frac{1}{4}(1+x)\frac{W_o}{M_o} .\qquad(16)$$

The assumption of rapid combustion at the flame yields zero concentrations of sodium vapor and oxygen gas as

$$\left.\begin{array}{l} Y_s = 0 \\ Y_o = 0 \end{array}\right\} .\qquad(17)$$

Combustion heat can be written by referring Eq. (15) in the expression

$$Q_b = \frac{1}{2}\left[(1-x)H_{Na_2O} + x H_{Na_2O_2}\right]\frac{W_s}{M_s} .\qquad(18)$$

This heat is partially consumed for evaporation of sodium and heat up of sodium vapor to temperature at the flame, and the remainder is transferred into the ambient gas by convection and radiation and oxygen gas arriving in the flame.  The equation of heat balance is, therefore, shown by

$$Q_b - W_s L - W_s C_{ps}(T_f - T_\ell)$$
$$= Q_c + Q_r + W_o C_{po}(T_f - T_g) ,\qquad(19)$$

where $L$ is latent heat of evaporation.

(5)  Determination of Unknown Parameters

When radius $r_\ell$ and flying velocity $V_p$ of the sodium particle, mole fraction of oxygen $Y_o$ and temperature $T_g$ in the ambient gas are to be given to the above-mentioned equations, unknown parameters are the combustion rate $W_s$ , the constants $A_1$ , $A_2$ , $B_1$ and $B_2$ appearing in the equations of mass diffusion and heat conduction, the temperature of the sodium particle $T_\ell$ , the radius $r_f$ and temperature $T_f$ of the flame. These parameters can be determined by following procedures.

(a)  The value of $W_s$ is given by substituting a guess value of $r_f$ into the equation

$$\frac{1+x}{4}\frac{W_s}{M_s} = 2\pi r_f \cdot S_f D_o \cdot N_o Y_o ,\qquad(20)$$

which is obtained from Eq. (11) and Eq. (16).

(b)  The constant $A_1$ becomes unity by comparing Eq. (5) with the equation

$$W_s = W_s [Y_s]_\ell - 4\pi r_\ell^2 \cdot S_s D_s \left[\frac{dY_s}{dr}\right]_\ell ,\qquad(21)$$

which is a combination of Eq. (1) with Eq. (2).  Thus, Eq. (5) at $r_f$ becomes

$$1 + A_2 e^{-\xi_f} = 0 ,\qquad(22)$$

which gives the value of $A_2$ .

(c)  Temperature $T_\ell$ is obtained from Eq. (5) at $r_\ell$

$$1 + A_2 e^{-\xi \ell} = \frac{P_s}{P_g} \qquad (23)$$

where $P_s$ is a function of $T_\ell$ .

(d)  Temperature $T_f$ is calculated from the equation

$$Q_b - W_s \left[ L + C_{ps} (T_f - T_\ell) \right]$$

$$= \left[ 2\pi r_f \cdot Nu \, k + \frac{1+x}{4} \frac{W_s}{M_s} M_o C_{po} \right] (T_f - T_g)$$

$$+ 4\pi r_f^2 \cdot \varepsilon_2 \sigma_s \left( T_f^4 - T_g^4 \right), \qquad (24)$$

which is derived from Eq. (13), (14) and (19).

(e)  The constants $B_1$ and $B_2$ are determined from Eq. (8) subjected to the boundary condition

$$\left. \begin{array}{l} B_1 + B_2 e^{-\lambda \ell} = T_\ell \\[6pt] B_1 + B_2 e^{-\lambda_f} = T_f \end{array} \right\} \qquad (25)$$

(f)  Check of guessed $r_f$ is made by the equation

$$W_s L = W_s C_{ps} B_2 e^{-\lambda \ell} + 4\pi r_\ell^2 \cdot \varepsilon_1 \sigma_s \left( T_f^4 - T_\ell^4 \right), \qquad (26)$$

which expresses heat transfer to the sodium particle to evaporate liquid sodium .  Iteration from (a) to (f) is made until both sides of Eq. (26) meet each other.

(6)  Model of Spray Combustion in Vessel

Calculations were made to obtain changes in pressure, temperature and oxygen concentration with time after spraying sodium into the closed vessel by dividing the space into nodes as shown in Fig. 9.  It is postulated that gas movement between nodes is not due to convection but to expansion of gas.  Heat transfer from the gas to the vessel wall is calculated for each node. After the end of sodium spray, decreases in pressure and temperature of the gas are determined by treating the gas space as one node.

Free falling motion is assumed to the motion of sodium particles injected with initial velocity $v_i$ from the spray nozzle.  Thus, when height of any node from the nozzle is between $Z$ and $Z + \Delta Z$ , it takes

$$\Delta t = \frac{1}{g} \left[ \sqrt{v_i^2 - 2gZ} - \sqrt{v_i^2 - 2g(Z + \Delta Z)} \right] \qquad (27)$$

for the sodium particle to pass through the node. If the decreasing rate of particle size can be put to be constant as in the combustion of fuel oil, decrease in the particle size $\Delta r_\ell$ during $\Delta t$ is approximately shown in the expression

$$\Delta r_\ell = r_\ell - \sqrt{r_\ell^2 - \left( \frac{d r_\ell^2}{dt} \right) \Delta t} \qquad (28)$$

Smaller size particles burn out during flying processes, but larger ones will remain without burning out to collide against the vessel wall and deposit thereon in the spray cone angle.  Deposited sodium will burn at a rate in proportion to oxygen concentration in the ambient gas.  In this case, combustion rate $W_d$ can be written in the form

$$W_d = \alpha Y_o W_w , \qquad (29)$$

where $\alpha$ is a constant and $W_w$ a depositing rate of sodium particles.

$$W_s = \frac{d}{dt}\left(\frac{4}{3}\pi r_\ell^3 \rho_\ell\right) = 2\pi r_\ell \rho_\ell K \qquad (31)$$

(1)  Combustion rate of Sodium Particle

The combustion rate of a single sodium particle was analyzed with using the model shown in Fig. 8.  For particle sizes, was used the log-normal distribution whose median diameter was 55 $\mu$ according to the data in Fig. 2.  Median diameters weighted by the diameter, surface area and volume respectively became 80, 300 and 670 $\mu$ , hence the particle size was changed from 5 $\sim$ 600 $\mu$ .  The oxygen concentration was chosen in the region from 5 $\sim$ 21 %, the ambient gas temperature up to 1,000 $^\circ$C and velocity of the particle up to 2 m/s.

It is reported that derivative of square of particle sizes with respect to time does not depend on the particle size in the case of fuel oil combustion.[16]  In comparison with fuel oil, sodium is larger in latent heat of evaporation and lower in vapor pressure.  However, results shown in Fig. 10 reveal that the derivatives are also insensitive to particle size of sodium.  This relation is expressed by

$$\frac{d r_\ell^2}{dt} \cong K \qquad (30)$$

The value of $K$ for sodium particles is in the order of $10^{-4}$ cm$^2$/s, as seen in Fig. 10, being about one-tenth of that for fuel oils.  Using Eq. (30), one can obtain the combustion rate $W_s$ in the form

Thus, the combustion rate per unit area

$$\frac{W_s}{4\pi r_\ell^2} = \frac{\rho_\ell}{r_\ell} K \qquad (32)$$

and the rate per unit mass is

$$\frac{W_s}{\frac{4}{3}\pi r_\ell^3 \rho_\ell} = \frac{3}{2}\frac{K}{r_\ell^2} \qquad (33)$$

Since these equations indicate that the combustion rate are proportional to the particle size, the differences seen among the parameters in Fig. 10 show an approximately linear increase in the combustion rates with the initial oxygen concentration in the ambient gas.  This fact is caused by increases in temperature of sodium particle and evaporation rate of sodium vapor.  The combustion rate also indicates increases with increases in the ambient gas temperature due to increases in the evaporation rate of sodium vapor, and with increases in convection velocity due to increases in the arriving rate of oxygen gas.

(2)  Comparison of Calculated Results with Those Observed

The change in pressure and oxygen concentration with time after spraying sodium into the closed vessel was analyzed with using the models described by Fig. 8 and 9.  The calculation was made for experimental runs in which initial temperature of sodium to be sprayed was 530 $^\circ$C, that in the ambient gas 10 $^\circ$C and oxygen concentration varying 0 $\sim$ 21 %.  By comparing calculated results with

those observed in experiments with spraying sodium into the gas atmosphere absent of oxygen, it was presumed that heat was transferred to the vessel wall with a convection rate of 7.2 $Kcal/m^2h°C$ and an emissivity of o.2.

The pressure and the oxygen concentration are represented in Fig. 11 as a function of time after spraying sodium into the vessel containing 6.5 % oxygen gas in nitrogen gas. The thick solid curve depicts the observed results and the thick broken curve the calculated ones. The thin broken line indicates change in the oxygen concentration. This figure shows that low oxygen concentration causes slow sodium combustion followed by mild pressure rise.

Similarly, data at 13 % and 21 % oxygen concentration are respectively represented in Fig. 12 and 13. These figures reveal that as the oxygen concentration is elevated, the combustion rate increases and the difference between calculated results and observed ones decreases. It is noted that both results are in good agreement particularly in the case of the combustion in the air. The difference observed in the final oxygen concentrations shows that considerable fraction of sodium will remain even in combustion of sprayed sodium. This is supported by the experimental results shown in Fig. 5.

4. Conclusions

(1) Experiment of Sodium Spray Combustion

(1-1) The gas pressure in the combustion vessel increases rapidly in the initial stage with injection of sodium spray, slowly reaches a peak before the end of spraying, and afterwards decreases gradually with time, in association with the change with time in gas temperatures in the vessel.

(1-2) The peak pressure depends more sensitively on the initial oxygen concentration in the gas atmosphere than the initial sodium temperature, but is far below a level calculated with use of ideal assumptions.

(1-3) Oxgen consumption observed in the experiment is not more than 80 % of that expected in complete combustion of sprayed sodium to become sodium oxide.

(1-4) The large defference between results obtained from the calculation and the experiment is accounted for the incomplete combustion of sprayed sodium and transfer of combustion heat to the vessel wall.

(2) Analysis of Sodium Spray Combustion

(2-1) The combustion rate per unit area on the sodium particle is in proportion to oxygen concentration in the ambient gas but in reverse to the particle size, and the decreasing rate of square of particle sizes is about 7 x $10^{-4}$ $cm^2/s$, being smaller in one order of the value of organic fuels.

(2-2) The peak pressure obtained from the calculation is 10 ~ 20 % higher than that observed in the experiment. Change in both pressures with time are on the whole in good ageement with each other.

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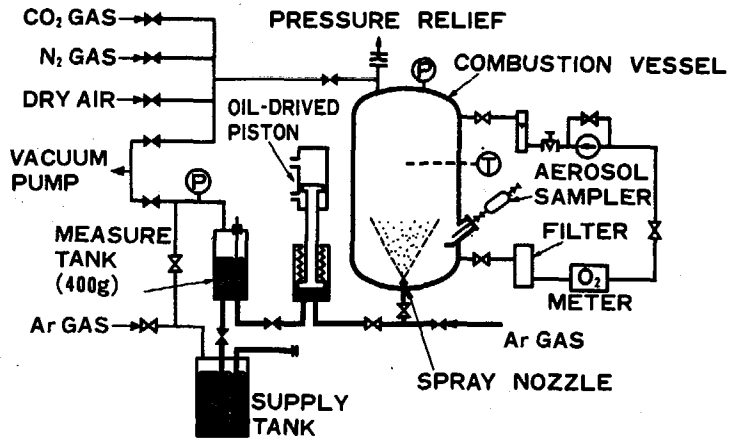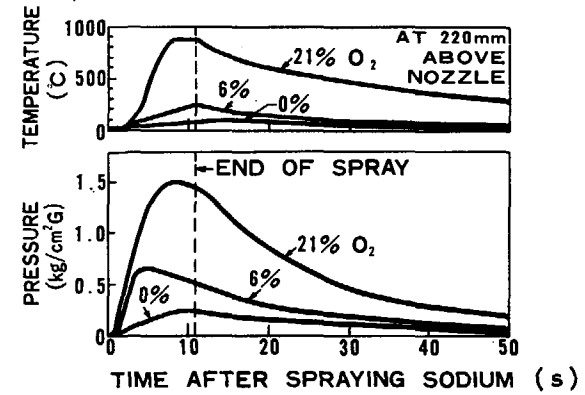
FIG. 1 ENERGY RELEASE TEST ARRANGEMENT
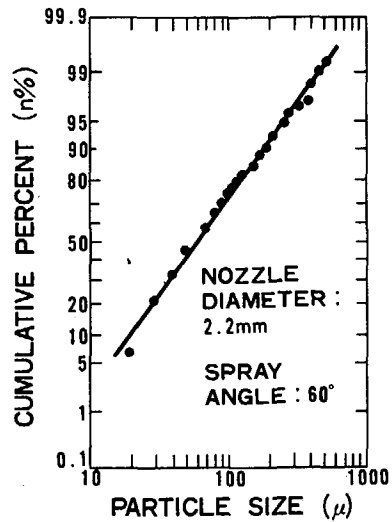


FIG. 3 TRANSIENTS OF TEMPERATURE AND PRESSURE



FIG. 2 PARTICLE SIZE DISTRIBUTION
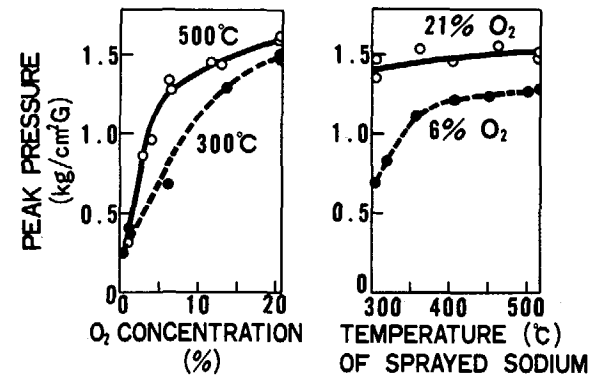OF SPRAYED SODIUM



FIG. 4 CHANGE IN PEAK PRESSURE

$$C.R.= \frac{\text{OXYGEN CONSUMPTION OBSERVED}}{\text{OXYGEN CONSUMPTION EXPECTED}}$$
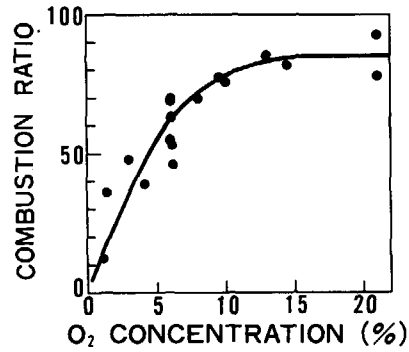IN COMPLETE COMBUSTION
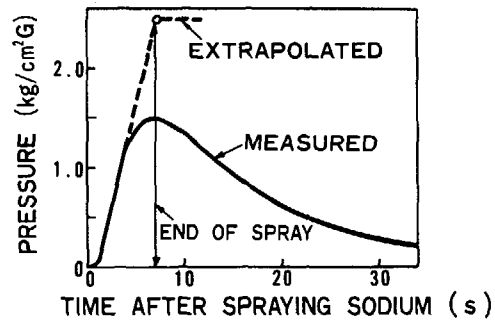
FIG. 5  COMBUSTION RATIO OF SPRAYED SODIUM
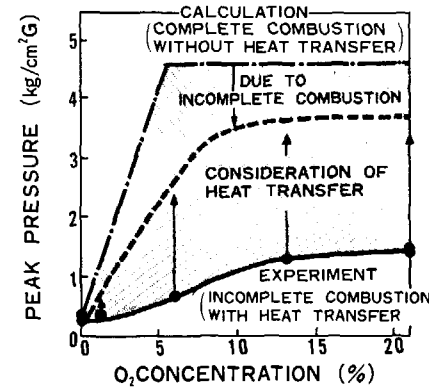
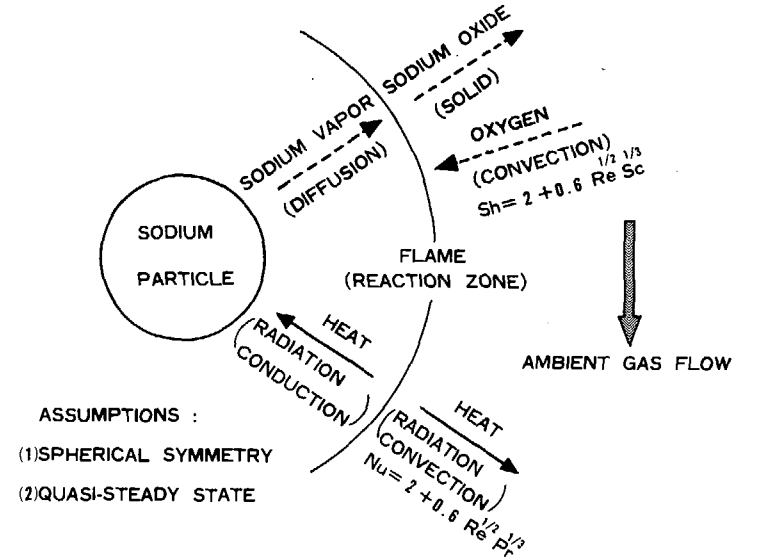FIG. 6  EXTRAPOLATION OF PEAK PRESSURE

FIG. 7  ACCOUNT OF COMBUSTION HEAT
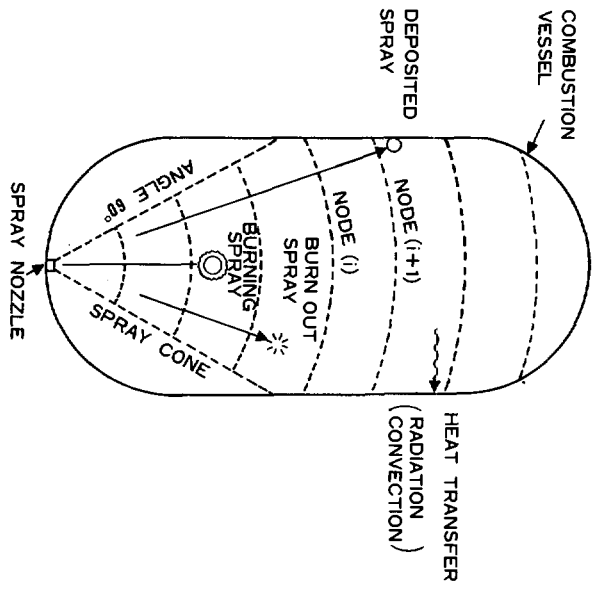
FIG. 8  MODEL OF SODIUM PARTICLE COMBUSTION

DECREASING RATE OF SQUARE
OF PARTICLE RADIUS (cm²/s)
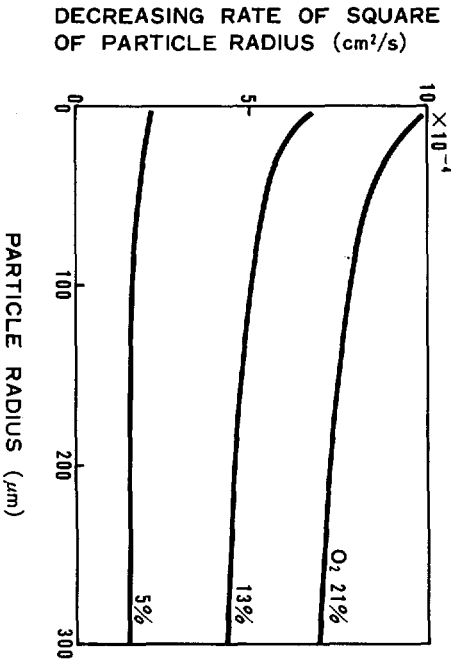
FIG. 10 DECREASING RATE OF SQUARE
OF SODIUM PARTICLE RADIUS

FIG. 9 MODEL OF SPRAY COMBUSTION IN VESSEL
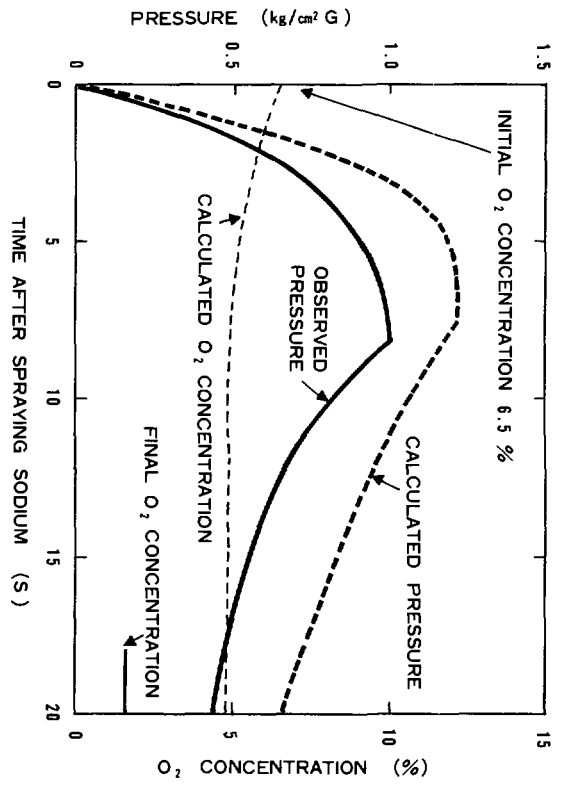
FIG. 11 CALCULATED AND OBSERVED RESULTS
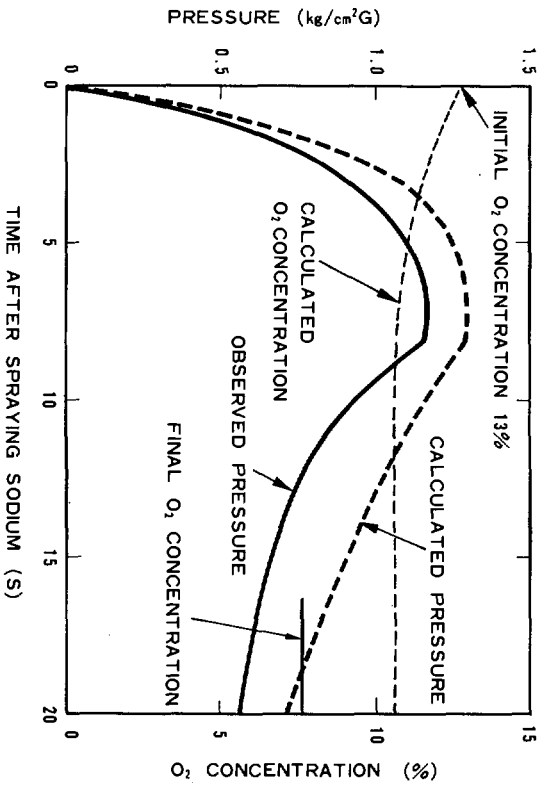
FIG. 12 CALCULATED AND OBSERVED RESULTS

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FIG. 13 CALCULATED AND OBSERVED RESULTS

# SODIUM SPRAY FIRES

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## ABSTRACT

Fundamental research on sodium spray fires is in progress
at the Cadarache Nuclear Safety Department (DSN) to
develop a computer code capable of predicting the
thermodynamic effects of such fires on the containment.
This paper discusses three types of phenomena which
require further examination in order to obtain more
realistic temperature and pressure results.

## 1 - INTRODUCTION

The thermodynamic effects of a sodium fire on the containment
depend on the type of combustion ( pool fire or spray
fire). The initial calculations for sodium spray
fires (1) were based on highly  simplified and pessimistic
assumptions, i.e. : instantaneous fire in an
adiabatic vessel, integral combustion, vessel temperature
uniformly raised by the combustion energy release, with
sodium monoxide as the only combustion product formed.
These hypothetical conditions result in high theoretical
pressure and temperature values : 8.12 bar max. and
2900 K max.

The purpose of this study is to develop a computer
code using less conservative hypotheses in an attempt
to obtain more realistic pressure and temperature values.
Three basic areas are open to more thorough investigation :

1 - Thermodynamic limitations, studied on the basis of
    a simplified  combustion model ; the major parameters
    analyzed and their effects are discussed below.
2 - Droplet ballistics, to introduce the concept of combustion
    efficiency, and therefore allowance for the amount
    of sodium capable of burning.
3 - Convective transport motion, which has not yet
    been fully investigated and will only be
    briefly mentioned in this paper.

## 2 - THERMODYNAMIC STUDY

The thermodynamic limitations were studied with
reference to a simplified combustion process, using
a flame temperature calculation based on the spherical
droplet combustion model (Figure 1).