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Sodium Fire Test at Broad Ranges of Temperature and Oxygen Concentrations (IV)

- Low Temperature Sodium Spray Tests -
(Translated Document)

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- Low Temperature Sodium Spray Tests -
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Sodium spray fire tests at an initial sodium temperature of 250℃ were conducted under the atmospheric conditions of air (21% oxygen) and nitrogen with 3% oxygen to determine both the sodium burning rate and the aerosol release fraction, and compare them with the test results at the initial sodium temperature of 500℃ in air atmosphere.

In the tests, sodium was supplied using a spray nozzle into a stainless steel vessel of 100 m^3 (SOLFA-2). The sodium burning rate was calculated from two independent methods: the consumption rate of oxygen in the vessel, and the enthalpy change in the vessel constituents during the test. The aerosol release fraction during the test was evaluated by the comparison between the measured aerosol concentrations and the calculations with the ABC-INTG code.

The main conclusions were as follows,

(1) In air atmosphere,
  a) sodium droplets ignited instantaneously and the spray fire was observed even under low initial sodium temperature of 250℃, and
  b) the sodium burning rate was about 400 g-Na/s and its fraction of supplied sodium flow rate was about 70%.

(2) In nitrogen atmosphere with 3% oxygen,
  a) ignition of sodium droplets was not observed under the 250℃ condition, and
  b) the sodium burning rate was about 44 g-Na/s and the fraction of supplied sodium flow rate was less than 10%.

Keywords: Sodium Fire, Spray, Fast Breeder Reactor

This document is a translation of JNC TN9400 2005-043 published in August 2005, written by Koji KAWATA, Takuo MATSUKI, and Shinya MIYAHARA.

広温度・広酸素濃度範囲 Na 燃焼試験（IV）
- 低温 Na スプレイ燃焼試験 -
(翻訳資料)

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（2011 年 12 月 14 日　受理）

初期温度が約 250℃のナトリウムを用いたスプレー燃焼試験を、空気雰囲気（酸素濃度 21％）と低酸素雰囲気（酸素濃度 3％）で行い、各々の条件におけるナトリウムの燃焼速度とエアロゾル放出割合を評価して、これまでに得ている初期温度約 500℃の条件における空気雰囲気でのナトリウムスプレー燃焼試験の結果と比較検討した。

試験は、内容積が 100m^3 の円筒型ステンレス鋼容器（SOLFA-2）内にスプレーノズルを用いてナトリウムを噴霧して行い、容器内の酸素濃度変化および各部温度変化から燃焼速度を求めた。また、エアロゾル放出割合は、エアロゾル挙動解析コード ABC-INTG によるエアロゾル濃度の解析結果を実験結果と一致させる方法で評価した。

主な結論は以下の通りである。

(1) 空気雰囲気試験
  a) Na 温度が 250℃と低温であっても、スプレー状に漏えいした場合は着火・燃焼する。
  b) Na 燃焼速度は約 400g-Na/s となり、Na 供給流量に対する割合は約 70％となる。
(2) 低酸素濃度雰囲気試験
  a）低酸素濃度雰囲気では、250℃の低温 Na がスプレー状に漏えいしても着火は生じない。
  b) Na 燃焼速度は約 44g-Na/s で、Na 供給流量に対する割合は 10％未満である。

本報告書は 2005 年 8 月に発行された報告書（JNC TN9400 2005-043：川田耕嗣、松木卓夫、宮原信哉）の翻訳である。
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1. Introduction

A sodium leak accident is included in the design basis events for fast reactor plants that use sodium as a coolant. Therefore, confirmation of the integrity and effectiveness of the systems to be provided in the plant against such accidents, as well as validation of the analysis codes to evaluate the thermal impacts of the sodium burning, are important tasks in order to secure the credibility of the fast reactor plants.

The Japan Nuclear Cycle Development Institute (JNC) has conducted a number of experimental studies using the SAPFIRE Facility at the Oarai Engineering Center. However, the sodium leak fire tests had been conducted so far at the high initial temperature of about 500 °C, mainly under the air atmosphere. In order to achieve a good balance between efficient design and safety for the fast reactor plant in the future, we need to obtain sodium burning behavior data in an extended condition range with respect to the initial sodium temperature, and oxygen concentration in the atmosphere. Particularly, for a low temperature sodium leak accident in the primary cooling system during the time periods other than the rated operation, the ex-vessel storage tank (EVST) and the maintenance cooling system, where the sodium temperature is relatively low in the fast reactor plant, it is necessary to confirm that the conventional sodium burning analysis code provides valid results with respect to thermal impacts both in the air atmosphere and a low oxygen concentration atmosphere.

In this study, spray fire tests were conducted using sodium at the initial temperature of about 250 °C in both air atmosphere (oxygen concentration of 21%) and low oxygen concentration atmosphere (nitrogen gas with 3 % oxygen). Sodium burning rates and the aerosol release fraction were estimated in each atmospheric condition to compare with the values at the initial temperature of 500 °C obtained to date.

2. Test apparatus and measurement

2.1 Test apparatus outline

The test apparatus used for the sodium spray fire test at the low temperature consists of a SOLFA-2 test vessel and its peripheral apparatus, including a sodium heating vessel (MH), an impurity sedimentation tank (DT: dump tank), a sodium storage tank (ST) and the exhaust smoke treatment system (Figure 1).

A maximum of approximately 4000 kg of sodium can be heated to the predefined temperature in the sodium heating vessel and fed to the test vessel by increasing the pressure of the nitrogen cover gas in the vessel. The dump tank was used to collect and store the sodium deposited on the sodium catch pan. The sodium storage tank stores the sodium and feeds it to the sodium heating vessel when it is used in the tests. The sodium aerosol generated during the tests is removed with a water scrubber and the HEPA filter of the exhaust treatment system to prevent the release of the aerosol into the atmosphere.

2.2 SOLFA-2 test vessel

The structure of the SOLFA-2 test vessel is shown in Figure 2. The vessel is a vertical cylindrical stainless steel air-tight container (SUS304, $25\mathrm{mm}^t$) with an internal volume of about 100 m^3. For the test, a spray nozzle was installed at the tip of the sodium feed pipe in the upper part of the vessel, and a stainless-steel (SUS304) sodium catch pan ($2900\ \mathrm{mm}^{\varphi}\times 350\ \mathrm{mm}^{H}\times 6\ \mathrm{mm}^{t}$) was installed 4 m below the nozzle to catch and reserve unburned sodium.

2.3 Measurement

The main features being measured, and their measurement points during the test, are shown in Figure 3. The temperature and flow rate of the sodium feed were measured with thermocouples and a magnetic flow-meter installed in the sodium feed pipe, respectively. Figures 4, 5 and 6 show the spatial arrangement of thermocouples set in the SOLFA-2 test vessel, in the gas region of the SOLFA-2 test vessel and in the sodium catch pan, respectively. The oxygen concentration was measured with the electromagnetic oxygen analyzer, and the hydrogen concentration with the thermal conductive hydrometers at three different heights in the test vessel (as shown in Figure 3). The sodium aerosol in the atmosphere was sampled by sucking about one litter of atmospheric gas with a vacuum cylinder via sintered metallic filters at two different heights in the test vessel (also shown in Figure 3). Settling aerosol was sampled by exposing the sampling pan intermittently for constant duration (1 minute) at a single point, inside the manhole of the test vessel.

2.4 Spray nozzle

The spray nozzle used in the test is shown in Figure 7. The specification of the nozzle was the same as the one used in the high temperature sodium spray fire test (Run-E1)1); the spray cone angle was approximately 25 degree, and the droplet diameter measured in a water test was approximately 2.6 mm (mean volume diameter) and 1.8 mm (mean surface diameter).

3. Test conditions and method

3.1 Test conditions

The main test conditions of this study, and those of the high temperature sodium spray fire test (Run-E1), are shown in Table 1. The tests were run in two cases, in the air (21% oxygen) (Run-E4-2), and the low oxygen concentration atmosphere (nitrogen gas with 3% oxygen) (Run-E4-1), to have consistency with the test conditions in the Run-E1 (except for the initial sodium temperature). Therefore, the droplet diameter and the spray cone angle obtained by the spray nozzle were nearly the same as those in the Run-E1[1)].

The initial sodium temperature was set at 250 °C to represent the low temperature, considering the temperatures in the prototype fast reactor Monju; 260 °C at the primary system (low oxygen concentration atmosphere) of the EVST cooling system, 240 °C at the secondary system (air atmosphere), and 230 °C at the secondary maintenance cooling system (air atmosphere). The duration of the sodium feed was determined to be 5 minutes, based on the estimated minimum time necessary for measurement.

Other test conditions were also the same as the Run-E1, including the height of the sodium spray nozzle and the presence or absence of an oxygen supply.

3.2 Test method

The two sets of tests were conducted consecutively; Run-E4-2 (a test in the air) at first, and then followed by the Run-E4-1 (a test in the low oxygen concentration atmosphere). This sequence was decided in order to avoid the effects on the second test of pool combustion of unburned sodium deposited and reserved in the catch pan during the first test. The test progression in the Run-E4 is shown in Table 2.

For the air atmosphere test (Run-E4-2), the sodium was transferred from the storage tank to the sodium heating vessel, and its temperature was raised and maintained at approximately 250 °C. Then, after confirming the test conditions such as the oxygen concentration in the test vessel, the cover gas pressure of the sodium heating vessel was adjusted to attain the predetermined sodium flow rate. The test was started by opening the sodium feed valve (VN-109). In order to keep the sodium feed rate constant during the test, the opening of the valve (VN-105) was controlled manually. The feeding of the sodium was completed in approximately five minutes. After the completion of the sodium feed, the safety status inside and outside the test vessel was confirmed, and the sodium reserved in the catch pan was drained to the dump tank by tilting the catch pan to transfer the reserved sodium as completely as possible to the drain pipe.

The measured data on the features shown in Figure 3 was recorded with the data logger (HP-1000) from the time before starting the feed of the sodium for the air atmosphere test, to the completion of the second low oxygen concentration atmosphere test. The interval of the data acquisition was 500 ms.

The combustion behavior during the tests was observed and recorded with a total of three video cameras. One camera was installed at the ceiling of the test vessel for the air atmosphere test, and second one was outside of the vessel for the low oxygen concentration atmosphere test to observe through the observation window on the side wall of the vessel. The last one, a high speed video camera, was also installed outside of the vessel to monitor the leak behavior during the air atmosphere test through the window on the side wall.

Sodium aerosol in the air was sampled every 30 seconds by inserting a sampling nozzle inside the vessel via a pipe platform on the side of the vessel. The settling aerosol was sampled at one-minute intervals with a special device in the form of spinning sample pan.

After completing the air atmosphere test, the sampling device was reinstalled for the low oxygen concentration atmosphere test when the temperature at each part and the pressure inside the vessel had returned to normal. The oxygen concentration inside the test vessel was then adjusted to the test condition; i.e. 3 %. As such, this test was conducted in the same way as the air atmosphere test.

After the completion of the two consecutive tests, the manhole on the side of the test vessel was opened. The photographs inside the vessel were taken. Sodium aerosol adhered to the inside wall of the vessel, and the residual sodium in the catch pan was then removed.

4. Test results and discussion

4.1 Air atmosphere test (Run-E4-2)

4.1.1 Burning behavior

The observation with the video camera installed inside the test vessel indicated instantaneous ignition of the sodium fed from the spray nozzle, and generation of a large amount of aerosol. This result was consistent with the observation in the sodium fire phenomenon test[2)] that indicated ignition temperature of 250 °C for the sodium with a droplet diameter of approximately 1 mm. The result is also consistent with the sodium leak accident at the solar energy plant in Almeria, Spain in 1987[3)] when sodium at a temperature of about 250 °C was sprayed and caused considerable damage.

Thus, we can conclude that sodium at the temperature as low as 250 °C can be ignited instantaneously when leaked as a spray into the air atmosphere. Also, the resulting behavior is the same as the spray fire of high temperature sodium at 500 °C.

4.1.2 Gas pressure in test vessel

Changes in the gas pressure inside the test vessel are shown in Figure 8 together with those of the Run-E1. In this test, the gas pressure reached the maximum of 0.098 MPa-gauge (1.0 kg/cm^2-gauge) two minutes after the start of the spraying operation. The maximum pressure was slightly lower than that of the Run-E1 (0.12 MPa-gauge (1.2 kg/cm^2-gauge)).

4.1.3 Gas temperature in test vessel

Figure 9 shows the time trends of the gas temperature inside and outside the spray cone, and at the upper part of the spray nozzle. The gas temperature inside the spray cone rapidly increased due to the immediate ignition of sodium droplets after starting the spraying operation and reached over 800 °C at the maximum. It then became lower with the decrease of the oxygen concentration in the vessel. The gas temperatures outside the cone and at the upper part of the spray nozzle reached approximately 500 °C and 550 °C respectively, due to heat transfer by the radiation from inside the cone and convection.

The gas temperatures in this test (shown in Figure 9) were slightly lower than those in the Run-E1 (shown in Figure 10), as found for the gas pressure described above.

4.1.4 Temperature of structures

The outer surface temperatures of ceiling and vessel side wall are shown in Figure 11. The temperature at the ceiling reached 80 °C at maximum, which is an increase of about 60 °C from the temperature at the test start. This temperature increase was almost half that of the corresponding position in the Run-E1 (about 130 °C). The maximum temperature of the side wall was 35 °C, an increase of approximately 15 °C from the temperature at the start. The temperature increase at the corresponding position in the Run-E1 was approximately 10 °C, which was lower than that in this test. This would be caused by the fact that the water-cooling jacket on the side wall was filled with cooling water in the Run-E1.

Figure 12 shows the change in the temperature at the sodium catch pan and the sodium pool. The temperature at the bottom of the sodium pool (1 mm above the sodium catch pan) reached approximately 700 °C at the completion of the spraying operation. At the point of 70 mm above the sodium catch pan near the sodium pool surface, the temperature was over 800 °C due to the radiation from the fire caused by the sodium pool burning. The temperatures of the sodium catch pan, with approximately 350 mm of an insulation layer at the bottom, reached to over 700 °C on both the front and back surfaces of the pan at the centre. It eventually became almost the same temperature as the sodium pool.

4.1.5 Oxygen concentration

Figure 13 shows the change in the oxygen concentration measured with three magnetic oxygen analyzers installed at different heights in the test vessel. The magnetic oxygen analyzer involves a consecutive sampling in order to eliminate sodium aerosol contained in the sampled gas, and to cool the gas. The gas sampling point and the measurement point are connected through piping. Therefore, there is a time lag between the sampling and measurement times. Figure 13, after correction for the time lag, indicates an earlier decrease in the oxygen concentration in the space under the spray nozzle than that in the space above the nozzle. This resulted in slight differences in oxygen concentration between the two. This could be explained by assuming that the oxygen in the space under the nozzle was consumed first by the sodium burning inside the spray cone, and the oxygen in the upper space was then transported to the lower space by the convection of gas to be consumed.

4.1.6 Sodium burning rate

The sodium burning rate was estimated based on the two methods described above: the change in the oxygen concentration in the test vessel, and the change in the temperature at each part of the vessel.

(1) Estimation method

a) Estimation from oxygen concentration

The number of oxygen moles in the vessel at a time (t) is expressed in the following equation,

$$N_{O2}(t) = [C_{O2}(t)/100 \cdot P(t) \cdot V] / [R \cdot T(t)] \quad \cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot \quad (1)$$

where

$N_{O2}(t)$: Number of oxygen moles in the vessel
$C_{O2}(t)$: Oxygen concentration in the vessel (%)
$P(t)$: Gas pressure in the vessel (Pa)
V : Vessel volume (m^3)
R : Gas constant ($kg\ m^2/s^2 mol\ K$)
$T(t)$: Gas temperature in the vessel (K)

The sodium burning rate can be determined by the following formula based on the oxygen consumption rate within the time increment Δt according to the Eq. (1),

$$B(t) \cdot \Delta t = [N_{O2}(t) - N_{O2}(t+\Delta t)] \cdot M_{O2} \cdot S \quad \cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot \quad (2)$$

where

$B(t)$: Sodium burning rate (kg-Na/s)
M_{O2} : Oxygen mass in one mol (kg-O_2/mol)
S : Mass of sodium that reacts with unit mass of oxygen (kg-Na/kg-O_2)

The ratio between reaction products of sodium and oxygen were assumed as below.

When $C_{O2} \geqq 11.3$ wt-%, $Na_2O : Na_2O_2 = 3 : 2$
When $C_{O2} < 11.3$ wt-%, $Na_2O : Na_2O_2 = 1 : 0$

b) Estimation from temperature change

A heat of combustion associated with the sodium burning is calculated based on the temperature changes in each part of the structures, which then are converted to the sodium burning rate.

$$B(t) \cdot \Delta t \cdot Q_{Na} + Q_S(t) = \sum[C_{pi} \cdot \Delta T_i(t)] \quad \cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot\cdot \quad (3)$$

where

Q_{Na} : Heat of combustion of unit mass of the sodium (kJ/kg-Na)
$Q_S(t)$: Heat from other heat sources (kJ)
C_{pi} : Heat capacity of structure (i) (kJ/°C)
$\Delta T_i(t)$: Temperature change of structure (i) during the time increment Δt (℃)

(2) Estimated results of sodium burning rate

The changes in the sodium burning rate over time obtained from the oxygen concentration change are shown in Figure 14, and that from the temperature change at each position in Figure 15. When these sodium burning rate values are averaged with time and converted to the value at the oxygen concentration of 21 % under the assumption that the burning rate is proportional to the oxygen concentration, the values become 387 g-Na/s from the both methods. This corresponds to about 70 % of the sodium feed rate of 540 g-Na/s.

It was reported that in the Run-E1 test the sodium burning rate was about 160 g-Na/s, which corresponded to about 30 % of the sodium feed rate. This burning rate is the value at the mean oxygen concentration of about 10 % over the time period when the sodium was sprayed. Also, a different reaction product ratio was assumed which determines the sodium mass (S) that reacts with the unit mass of oxygen in this test. When converting these values for the oxygen concentration of 21 %, the sodium burning rate becomes about 500 g-Na/s which is almost equal to the sodium feed rate.

Figure 16 shows the fraction of the sodium burning rate to the sodium feed rate as a function of the initial sodium temperature. Here, the used burning rate is the converted value under the condition of 21 % oxygen concentration. The figure also contains the result of the Run-E3-3 as a reference, which is the sodium burning test[4)] of columnar, rod-like sodium leak flow, performed under almost the same test conditions with this Run-E4-2 and Run-E1. The figure indicates that the burning rate of the sodium sprayed at the low temperature (initial temperature of 250 °C) was lower by about 30 % compared to that sprayed at the high temperature (500 °C), but higher than that of the columnar leak and combustion at the high temperature of 500 °C.

4.1.7 Aerosol release fraction

The aerosol release fraction, α, was evaluated by comparing the aerosol concentration and the settled aerosol amount between the aerosol behavioral analysis code ABC-INTG and the test results. The release fraction used in the analyses was 30 %, based on the knowledge obtained to date; about 20-40 % of the burning rate for the sodium pool fire and 20-30 % of the burning rate for the sodium leakage with a columnar leak. Other main analysis conditions shown below were those obtained from the sodium burning test for the columnar leak[4)].

Mean aerosol radius r_g : 1.5 μm
Aerosol density ρ : 1.0 g/cm^3
Factor ε to be multiplied to the gravitational condensation shape factor : -1

The comparisons between the test result and simulation result are shown in Figure 17 for the suspended aerosol concentration and in Figure 18 for the settled aerosol amount. Figure 17 shows that the suspended aerosol concentrations of the test result were far below that of the simulation result in the first 1 minute after starting the spraying operation, and the results of test and simulation were approximately in good agreement from after two minutes until the end of the spraying operation. The reason for this was considered that, in the test, the aerosol had not evenly dispersed inside the test vessel after starting the spraying operation, and the suspended aerosol concentrations were low at the sampling points; whereas, in the analysis, the suspended aerosol was assumed to be evenly dispersed in the space inside the vessel. With regards to the settled aerosol amount (Fig. 18), the calculation result was lower than that of the test over the entire spraying period. This could be due to the entrainment of unburned sodium droplets leaked as a spray to the sampling pan.

Thus, we conclude that the aerosol behavior analysis assuming the aerosol release fraction of about 30% reproduces fairly well the change in the suspended aerosol concentration of the test result.

4.2 Low oxygen concentration test (Run-E4-1)

4.2.1 Burning behavior

We observed with a video camera the burning behavior of sprayed sodium at the initial temperature of 250 °C in the low oxygen concentration atmosphere (3 %). The video image shows that the sprayed sodium droplets, different from those in the air atmosphere test (Run-E-4-2), were settled without being ignited. They simply generated aerosols. The image also indicated that the cone angle formed by the spray nozzle was about 27 degrees, which was almost the same as the angle obtained from the water test of about 25 degrees.

4.2.2 Gas pressure in test vessel

The change in the gas pressure inside the test vessel is shown in Figure 8. The maximum gas pressure in this test was about 0.05 MPa-gauge (0.5 kg/cm^2-gauge), which was half of the pressure in the air atmosphere test (about 0.098 MPa-gauge (1.0 kg/cm^2-gauge)) as described above. This is because sodium was not ignited in the low oxygen concentration atmosphere, as was apparent from the observation of the burning behavior. Therefore, the maximum gas pressure in this test was lower than that in the air atmosphere test in which sodium was ignited and burned.

4.2.3 Gas temperature in test vessel

The changes in the gas temperature inside the test vessel are shown in Figure 19 for inside and outside the spray cone, and at the upper part of the spray nozzle. The maximum temperature inside the spray cone was about 350 °C, which was higher than the initial temperature of the leaked sodium of 250 °C. This fact indicates that the leaked sodium was not ignited under the low oxygen concentration atmosphere, but an exothermic reaction occurred due to the oxidation by the existing 3 % oxygen contained in the atmosphere.

The maximum gas temperature outside the spray cone and at the upper part of the spray nozzle remained lower than the temperature of the leaked sodium. The temperature was higher at the upper part of the nozzle than outside the spray cone.

4.2.4 Temperature of structures

The temperatures at the ceiling and the outer surface of the test vessel are shown in Figure 20. Since this test was conducted successively after the air atmosphere test, the initial temperatures of those positions were higher than the room temperature. However, the increase in the temperature during the test was about 10 °C at the ceiling, and less than 5 °C at the outer surface. Each of these was lower compared to those in the air atmosphere test.

Figure 21 shows the temperature change in the sodium catch pan and the sodium pool. The initial temperature at the bottom of the sodium pool (1 mm above the sodium catch pan) was as high as about 100 °C because a small amount of sodium remained from the air atmosphere test. However, the temperature was increased to only 250 °C, i.e. the sodium feed temperature, even following the completion of the spray. On the other hand, the temperature reached over 500 °C about one minute after starting the spraying operation near the surface of the sodium pool (70 mm above from the sodium catch pan). The reason for this was considered to be due to the settlement of high temperature sodium droplets heated by exothermic reaction by oxidation. The temperature of the sodium catch pan became very similar to that of the sodium pool since there was an insulation layer with a thickness of about 350 mm below the catch pan.

4.2.5 Oxygen concentration

The change in the oxygen concentration is shown in Figure 22. The oxygen concentrations inside the test vessel were different depending on the location in the vessel because of some residual effects by the previous air atmosphere test. The oxygen consumption speed during the spray was larger at the lower part of the test vessel, and was almost the same at the middle and the upper parts.

4.2.6 Sodium burning rate

The sodium burning rate was calculated from the oxygen concentration change and temperature change in each part, as was used in the air atmosphere test. The sodium burning rate estimated from the oxygen concentration change is shown in Figure 23. The figure indicates that the sodium burning rate in the low oxygen concentration test obtained from the oxygen analyzer (CO-101) placed at the lower part of the test vessel showed a slightly higher value than the others. The sodium burning rates obtained from the temperature change at each position of the vessel are shown in Figure 24. The mean burning rate during the spray period was about 45 g-Na/s, which was almost equal to about 43 g-Na/s-the average sodium burning rate obtained from the oxygen concentration changes in the three oxygen analyzers. Therefore, the sodium burning rate estimation was considered to be valid. The sodium burning rate was less than 10 % of the sodium feed rate. The results are shown in Figure 16 where the fraction of the sodium burning rate to the sodium feed rate is shown as a function of the initial sodium temperature. It is implied in the figure that the fire suppression effect is greater in the case of reducing the oxygen concentration than the case of decreasing the sodium initial temperature.

4.2.7 Aerosol release fraction

Similar to the air atmosphere test, the aerosol release fraction was evaluated by the comparison of aerosol concentration and settled aerosol amount between simulation and test results. The aerosol release fraction was assumed to be 20 % in the simulation because the fraction in the previous pool fire tests under the low oxygen concentration5) was approximately 20 %. The comparison between the simulation and test result are shown in Figure 25 for the aerosol concentration and in Figure 26 for the settled aerosol amount. The figure shows good coincidence for the aerosol concentration, while the simulated result was lower than the test result over the entire period for the settled aerosol amount. The reason for this was considered to be due to the entrainment of a part of leaked sodium droplet, in a similar manner to the air atmosphere test.

5. Conclusions

We conducted two cases of spray burning tests with low temperature sodium at approximately 250 °C; under air atmosphere and low oxygen concentration atmosphere (3%), and estimated the sodium burning rate and the aerosol release fraction in each case. The results are shown below:

5.1 Air atmosphere test

(1) Under the air atmosphere, the sodium is ignited and burned if leaked as a spray even when the sodium temperature is as low as 250 °C.
(2) The sodium burning rate was approximately 400 g-Na/s, almost 70 % of the sodium feed rate.
(3) The aerosol behavior analysis could reproduce the concentration change of the suspended aerosol in the test by assuming the aerosol release fraction in the sodium burning rate as being 30 %.

5.2 Low oxygen concentration atmosphere test

(1) Under the low oxygen concentration atmosphere, the sodium at the temperature as low as 250 °C was not ignited even when leaked as a spray.
(2) The sodium burning rate was approximately 44 g-Na/s, which was less than 10 % of the sodium feed rate.
(3) The aerosol behavior analysis could reproduce the concentration change of aerosol in the test, assuming the aerosol release fraction for the sodium burning rate as being 20 %.

From the above findings, we could assume that the sodium would be ignited and burned when the low temperature sodium at 250 °C would be leaked as a spray into the air atmosphere. The burning behavior would be similar to the case where high temperature sodium at about 500 °C leaked as a spray. By contrast, sodium would not be ignited and make moderate burning behavior in the low 3 % oxygen concentration atmosphere.

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References

1) T. Morii, et al. : "Large-Scale Test on Sodium Leak and Fire (III) (Large-Scale Test of Sodium Spray Fire in Air, Run-E1)", PNC TN9410 86-124Tr (1987).
2) K. Kawata, et al. : "Sodium Fire Test at Broad Ranges of Temperatures and Oxygen Concentrations (1) Effect of Leak Patterns on Ignition Temperatures", PNC TN9410 88-004 (1988). [in Japanese]
3) V. P. Luster, K. F. Freudenstein : "Feedback from Practical Experience with Large Sodium Fire Accidents", IAEA/IWGFR Technical Committee Meeting on Evaluation of Radioactive Materials Release and Sodium Fires in Fast Reactors, IWGFR/92 (1996).
4) S. Ohno, et al. : "Sodium Columnar Leak and Fire Tests – Combustion Rate and Aerosol Release Rate-", PNC TN9410 89-154 (1989). [in Japanese]
5) K. Kawata, et al. : "Sodium Fire Test at Broad Ranges of Temperature and Oxygen Concentration (II) – The Sodium Burning Rate and Aerosol Release Rate in Nitrogen Atmosphere", PNC TN9410 88-164 (1988). [in Japanese]

Table 1　Test conditions of Run-E4 and Run-E1

Items	Run－E4－1	Run－E4－2	Run－E1
Sodium Temperature	248℃	249℃	505℃
Spray Flow Rate	38.4 ℓ／min	39.4 ℓ／min	36.7 ℓ／min
Mass of Supplied Sodium	192 ℓ	197 ℓ	1101 ℓ
Spray Duration	5.1 min	5.1 min	30 min
Height of Falling Nozzle	4 m	4 m	3.98 m
Mean Droplet Diameter (1) Surface Mean Diameter (2) Volime Mean Diameter	 1.84 mm 2.58 mm	 1.84 mm 2.58 mm	 1.6 mm 2.2 mm
Initial Oxygen Concentration	3.3 %	20.8 %	21 %
Initial Relative Humidity	< 1 %	7 %	―――
Gas Pressure	Atmospheric Pressure		
Vessel Volume	100 m³		

Table 2 Test progression in Run-E4

Time	Test Progression
2/28 8:58	Sodium Charge in Sodium Heater Tank
10:21	Start of Data Recording
10:25	Start of Sodium Feed for Run-E4-2
10:30	Stop of Sodium Feed
10:50	Drain of Remaining Sodium in Pan
15:28	Start of Sodium Feed for Run-E4-1
15:33	Stop of Sodium Feed
15:34	Drain of Remaining Sodium in Pan
19:00	Stop of Data Recording

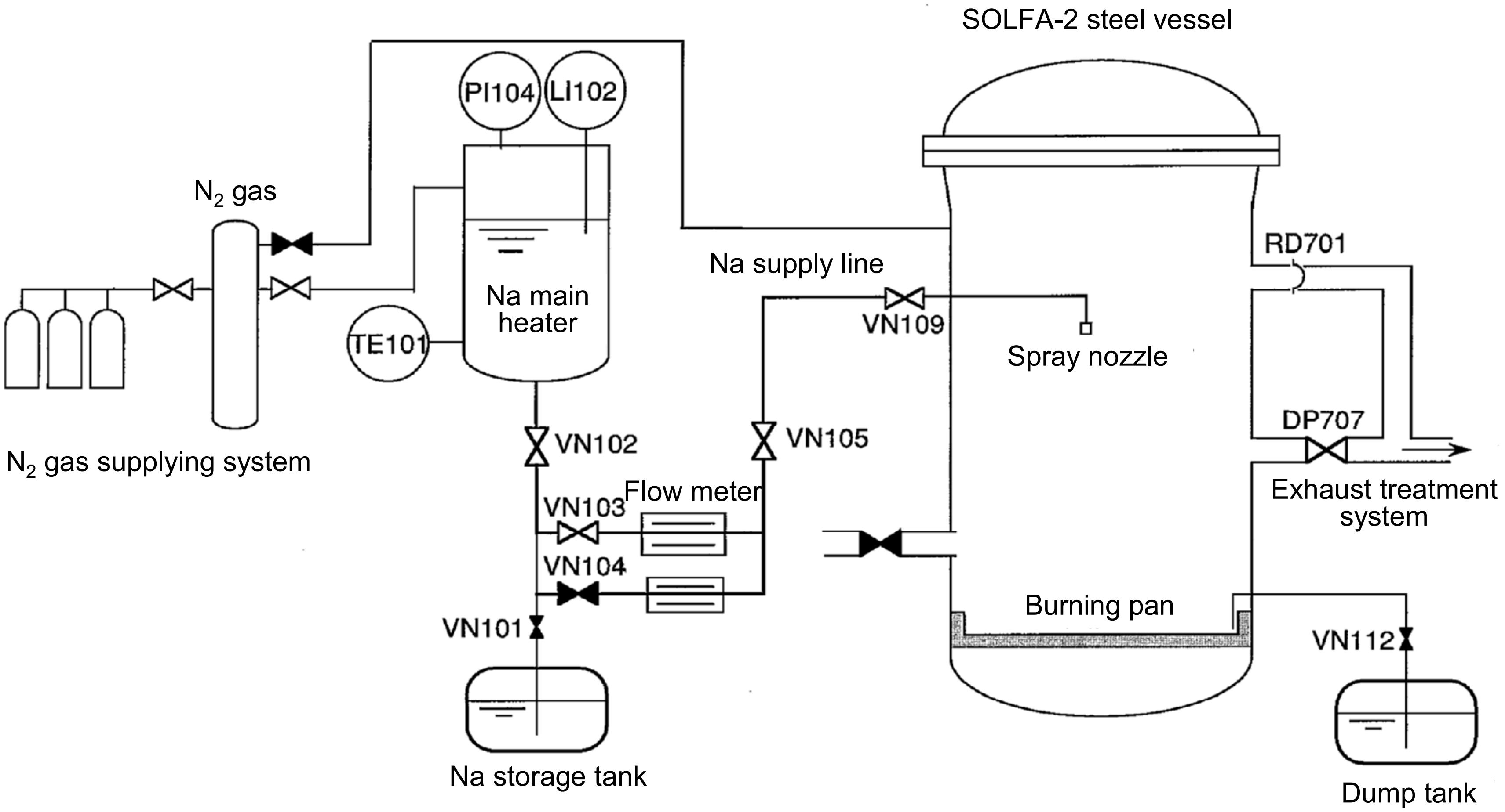
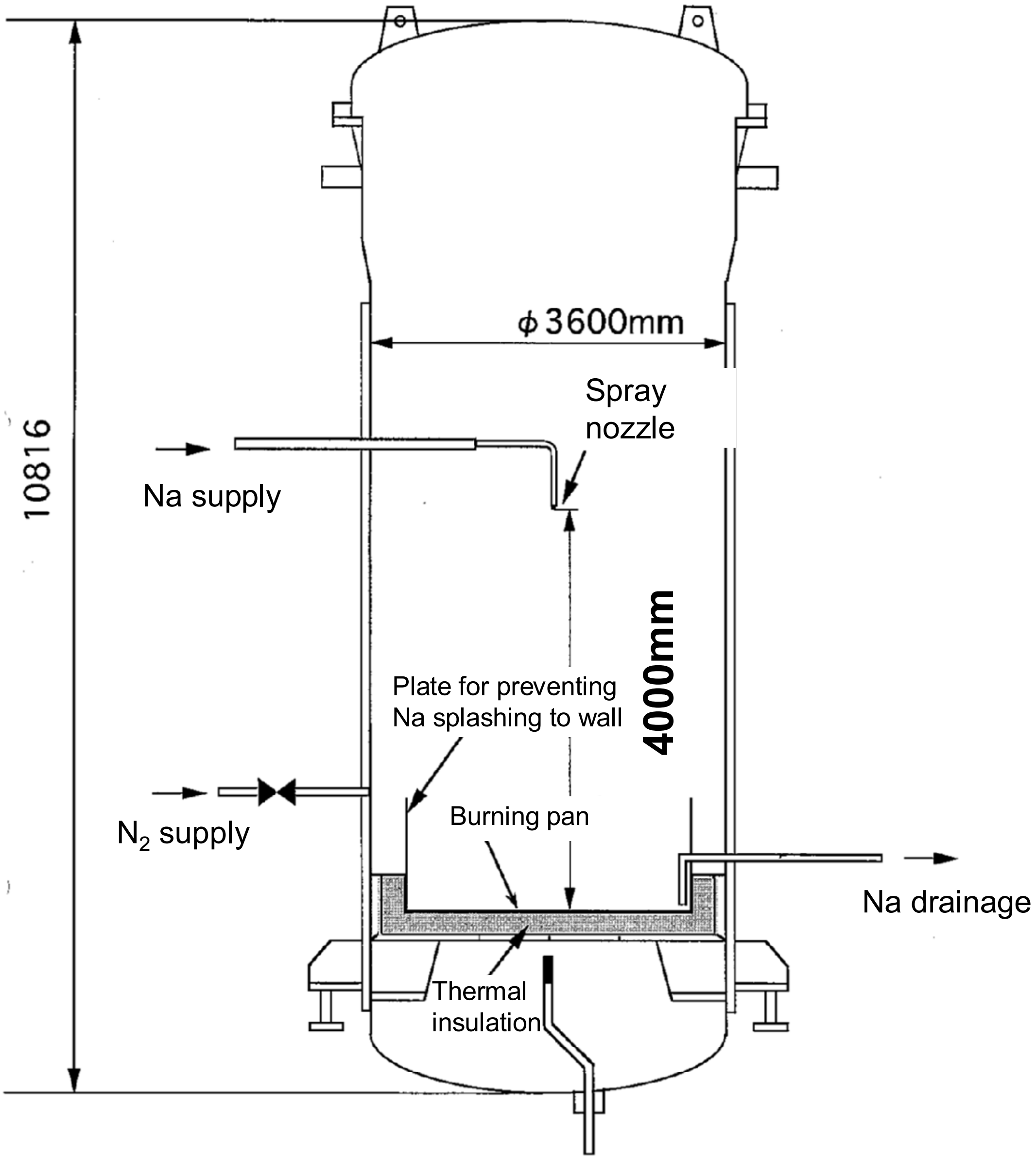


Fig. 1 Configuration of test apparatus in Run-E4



SOLFA-2 steel vessel (approx. 100m^3)

Fig. 2 SOLFA-2 test vessel

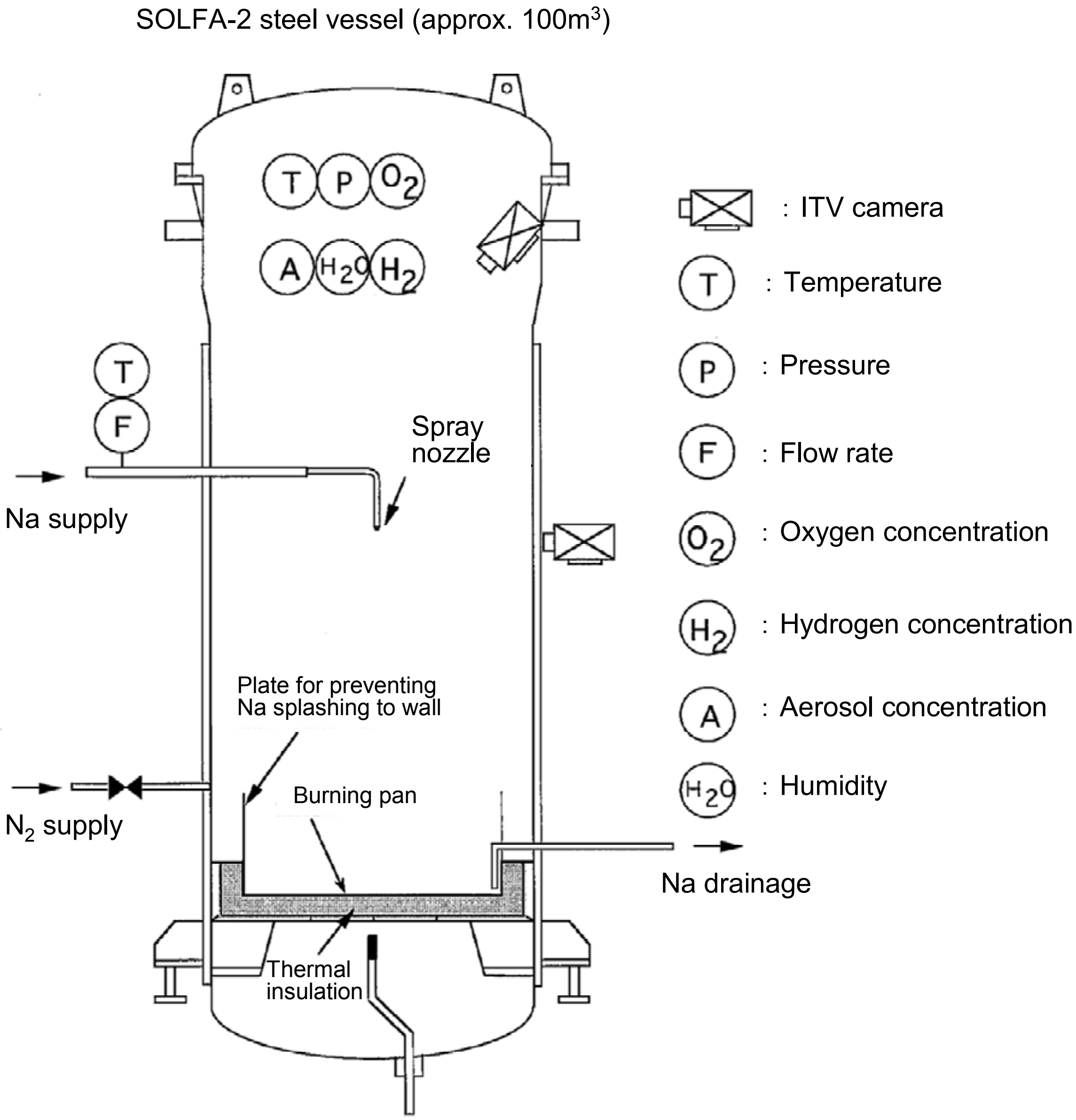


Fig. 3 Measurement in Run-E4

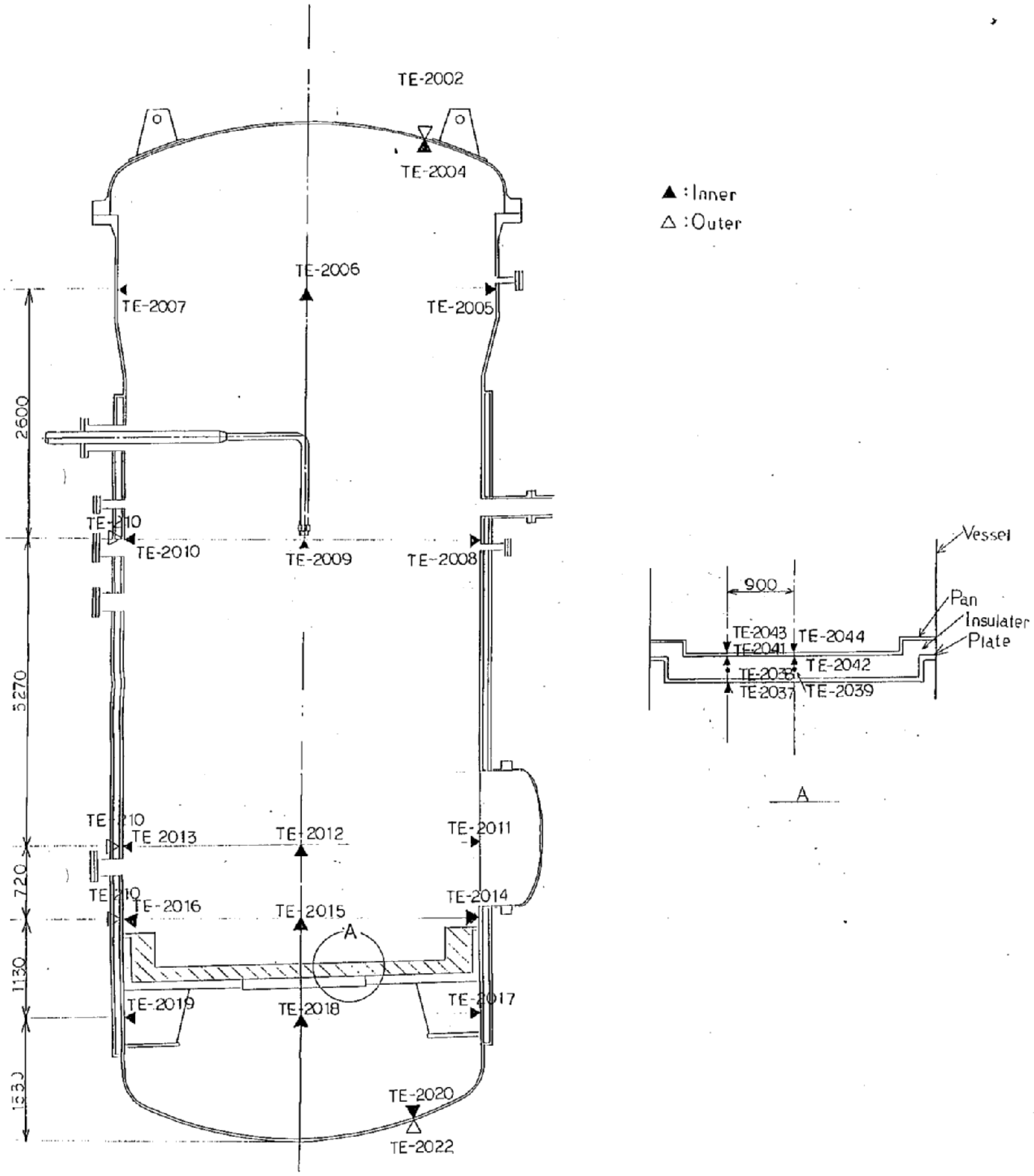


Fig. 4 Spatial arrangement of thermocouples in SOLFA-2 test vessel

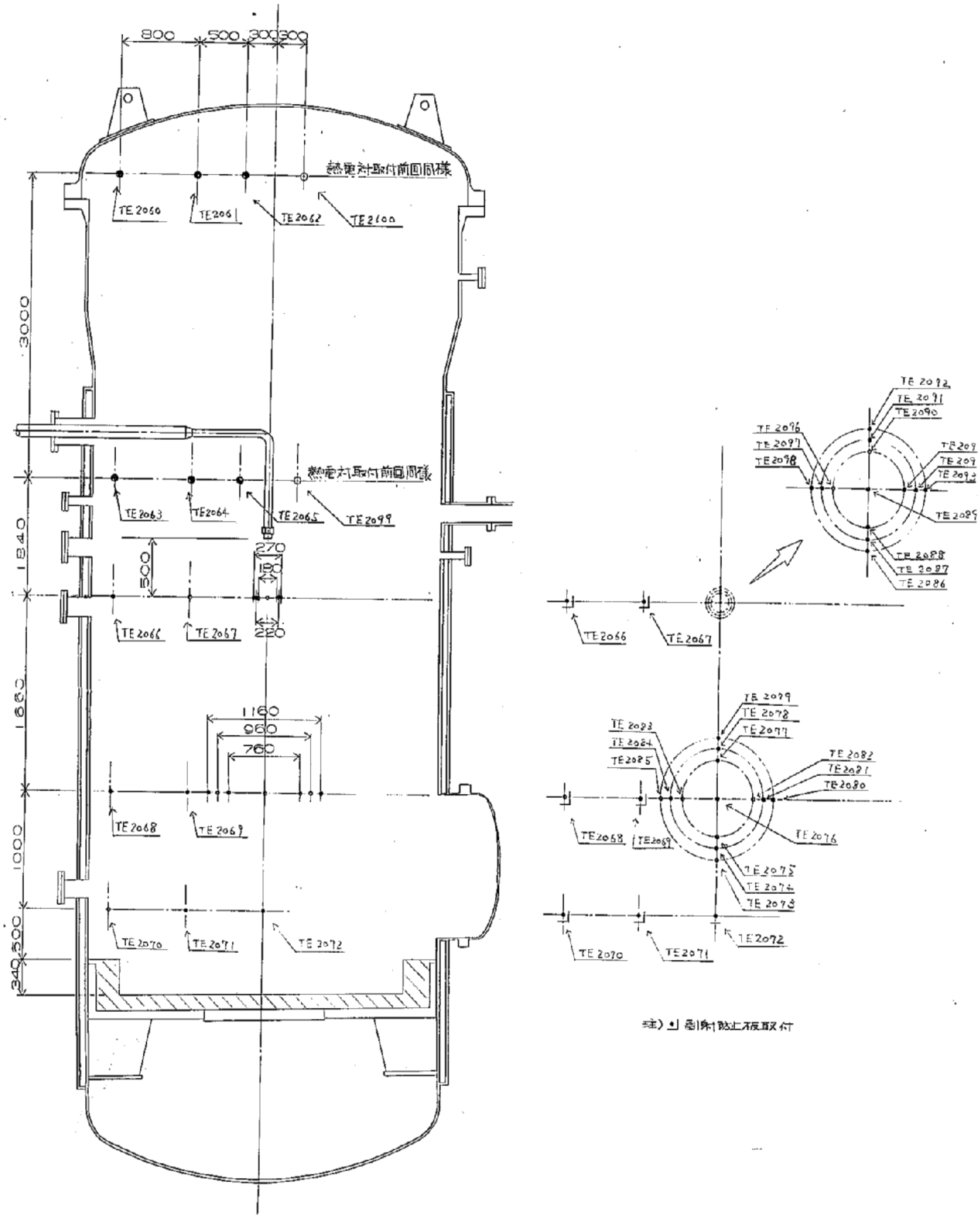


Fig. 5 Spatial arrangement of thermocouples in gas region in SOLFA-2 test vessel

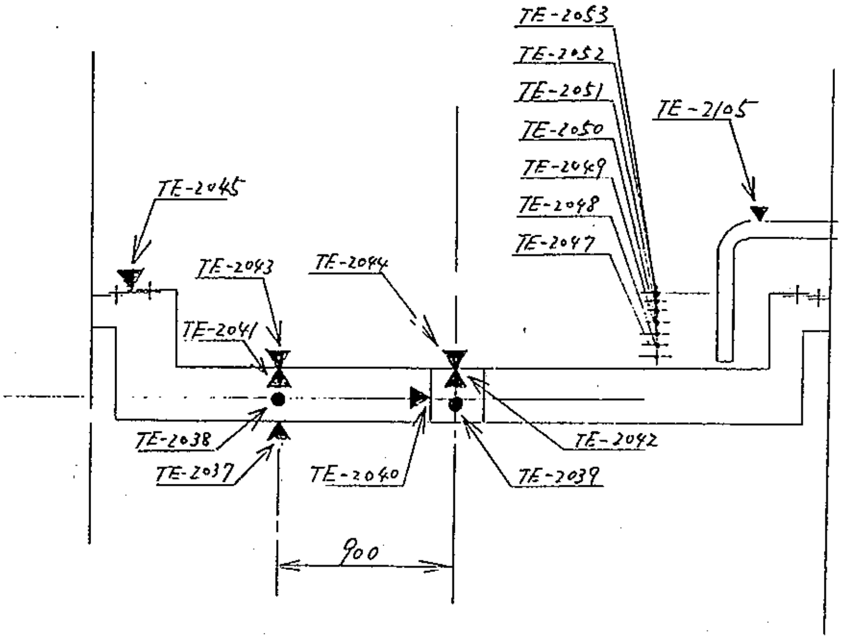


Fig. 6 Spatial arrangement of thermocouples in sodium catch pan

Test Results (Water)

( ) : Calculated as a sodium

	Condition
Nozzle Type	1EX4400-0N
Spray Patern	Full Cone
Pressure	1.5 kg/cm²
Flow Capacity	36.2 ℓ/min
Spray Angle	25°
Mean Surface Diameter	1.8 mm
Mean Volume Diameter	2.6 mm

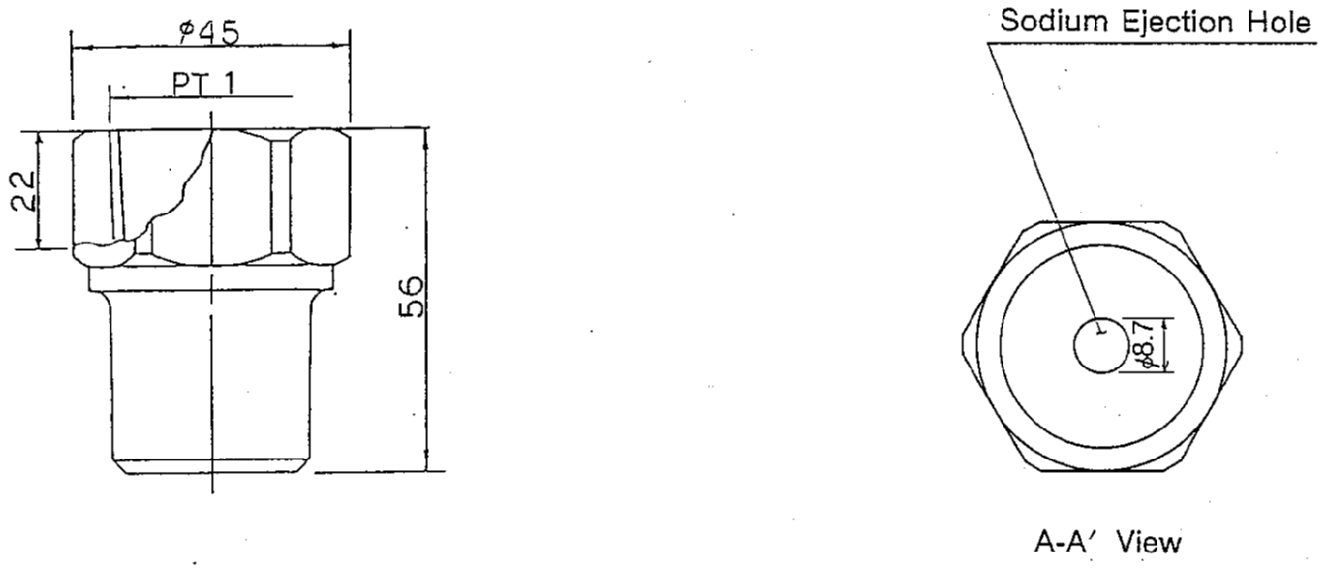


Fig. 7 Spray nozzle used in test

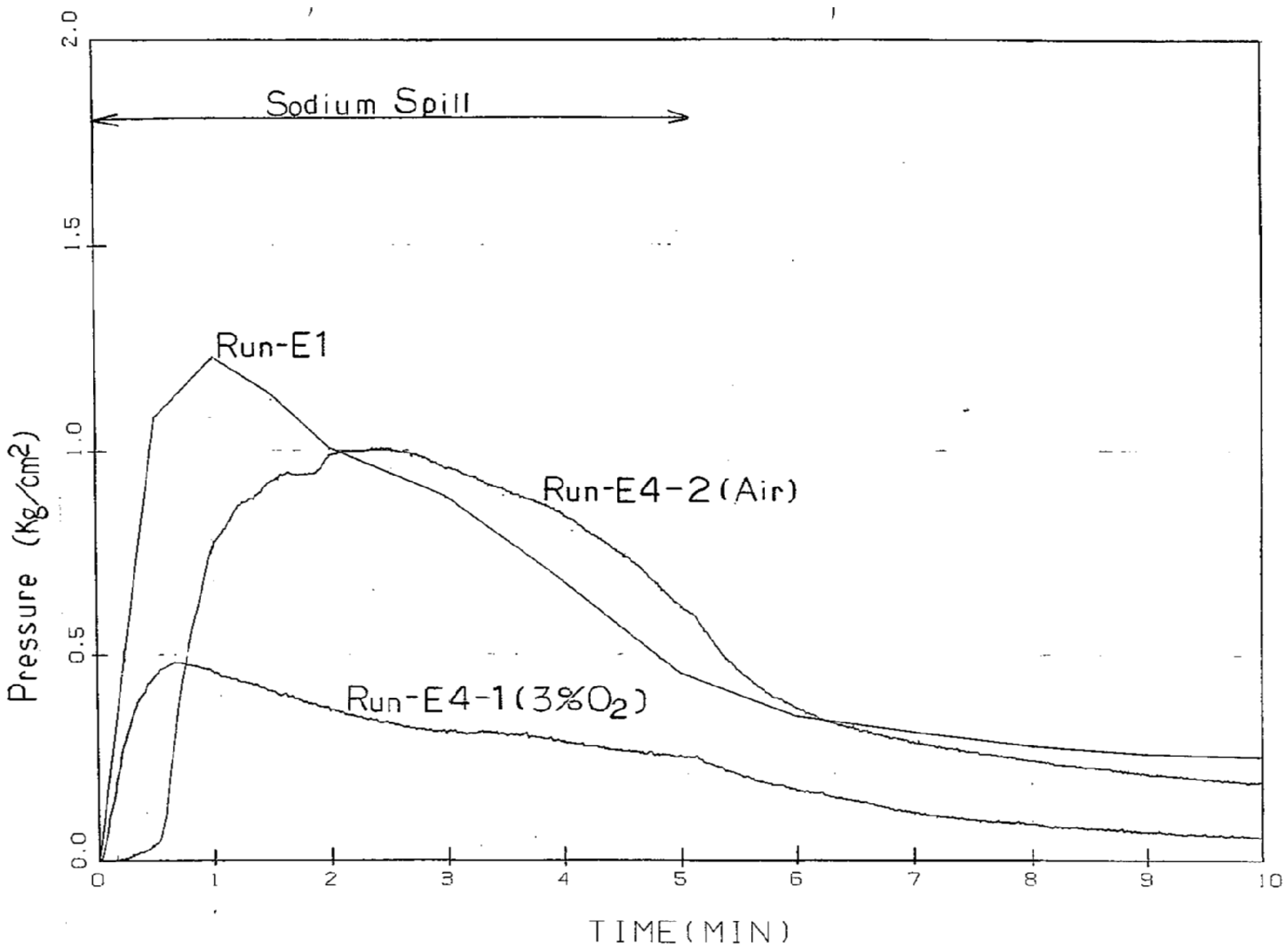


Fig. 8 Gas pressure in test vessel for Run-E1, Run-E4-1, and Run-E4-2

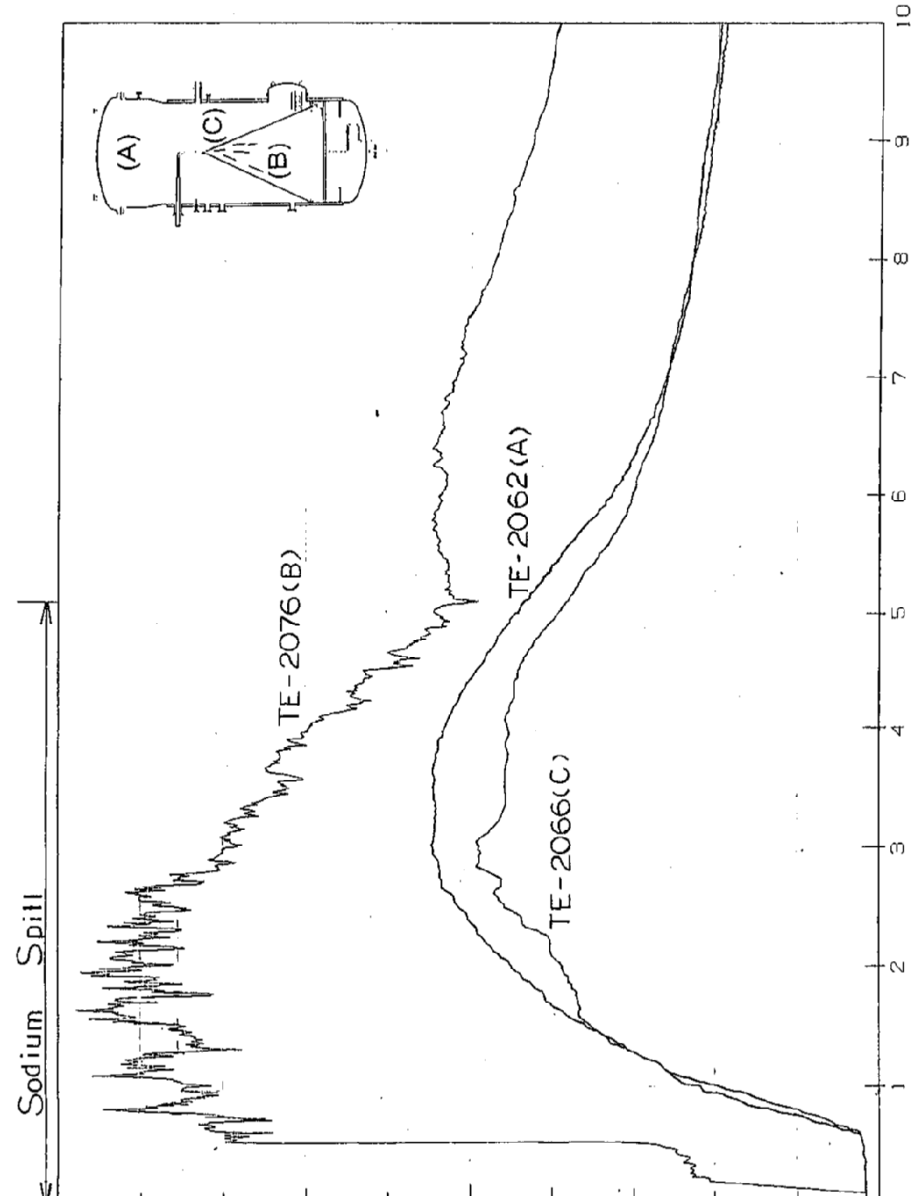


Fig. 9 Gas temperature in the vessel for air atmosphere test

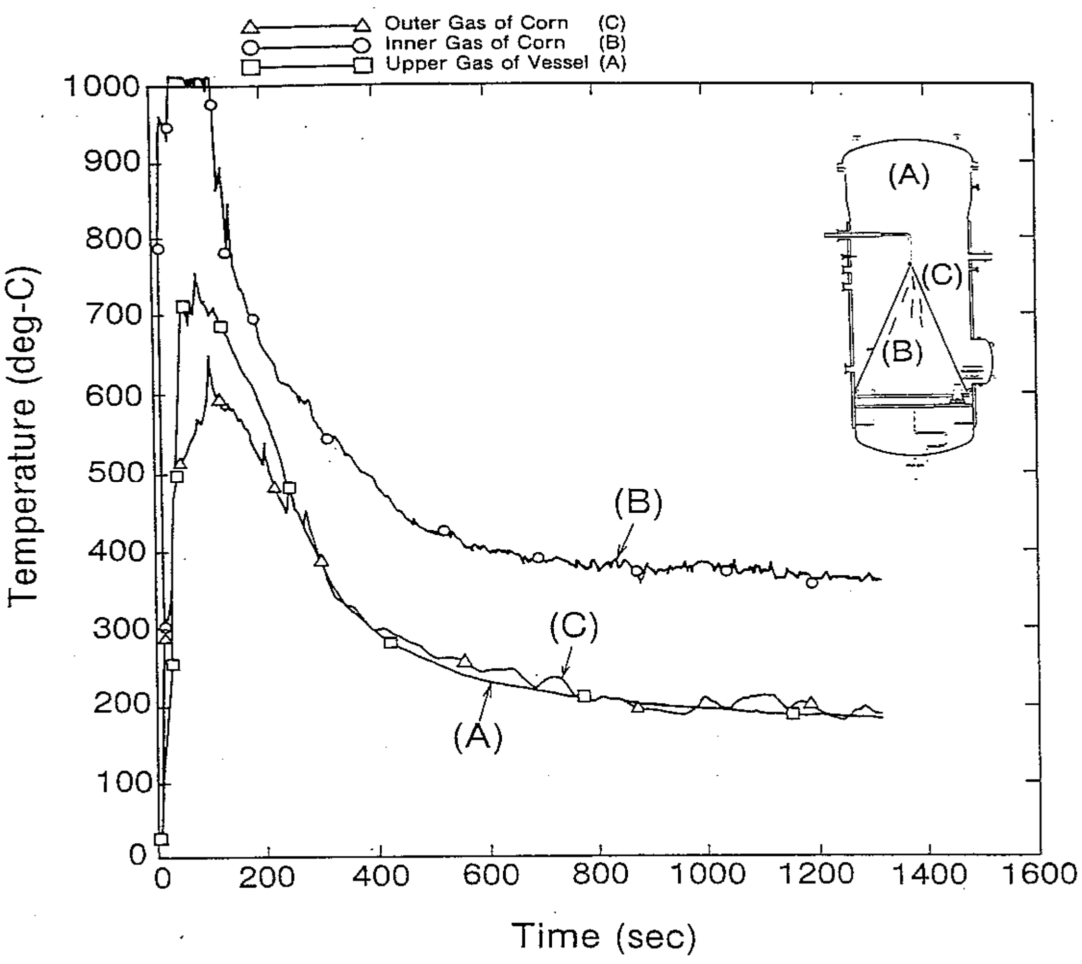


Fig. 10 Gas temperature in the vessel for Run-E1 test

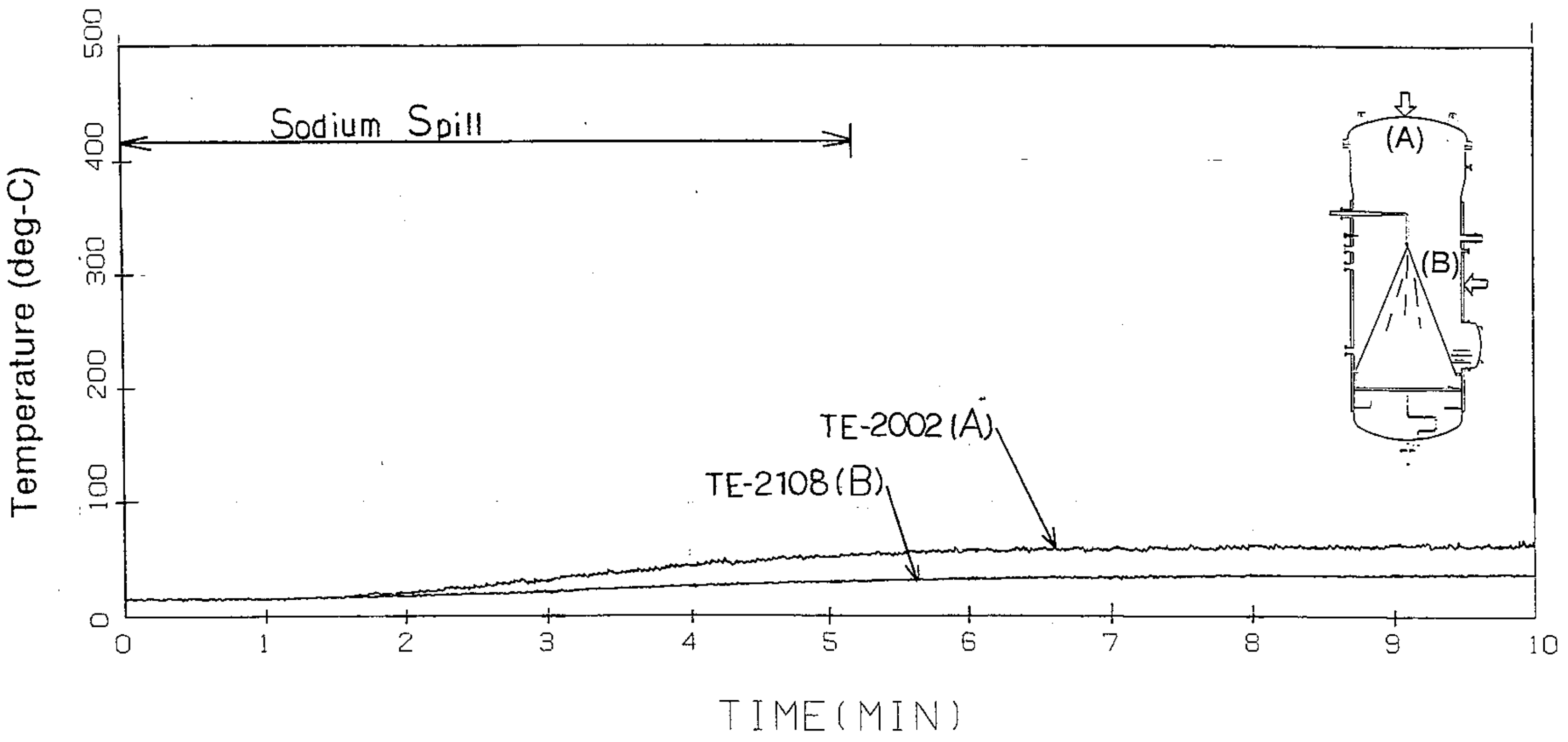


Fig. 11 Outer surface temperature of the vessel in air atmosphere test

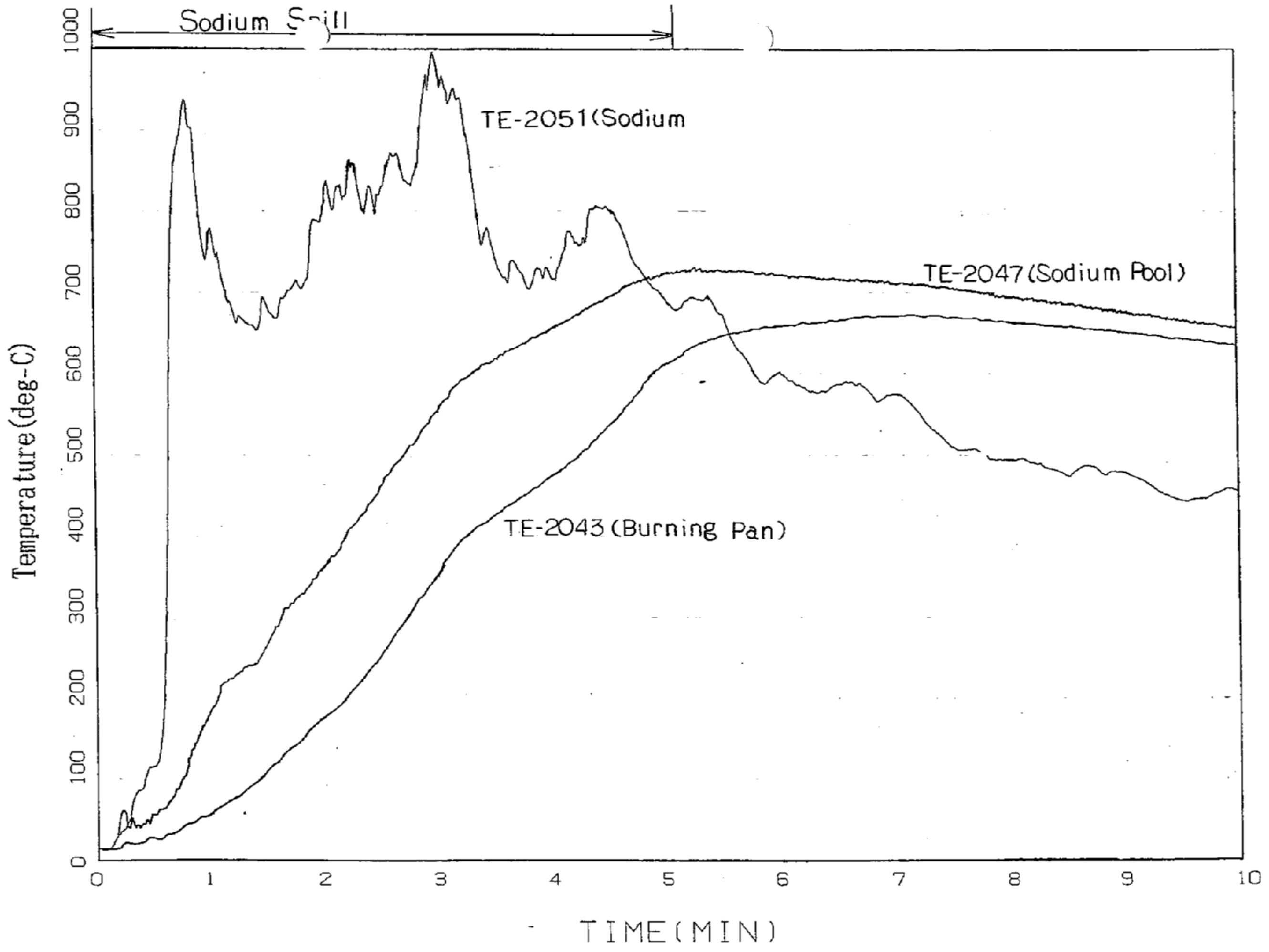


Fig. 12 Temperature of sodium catch pan and of sodium pool in air atmosphere test

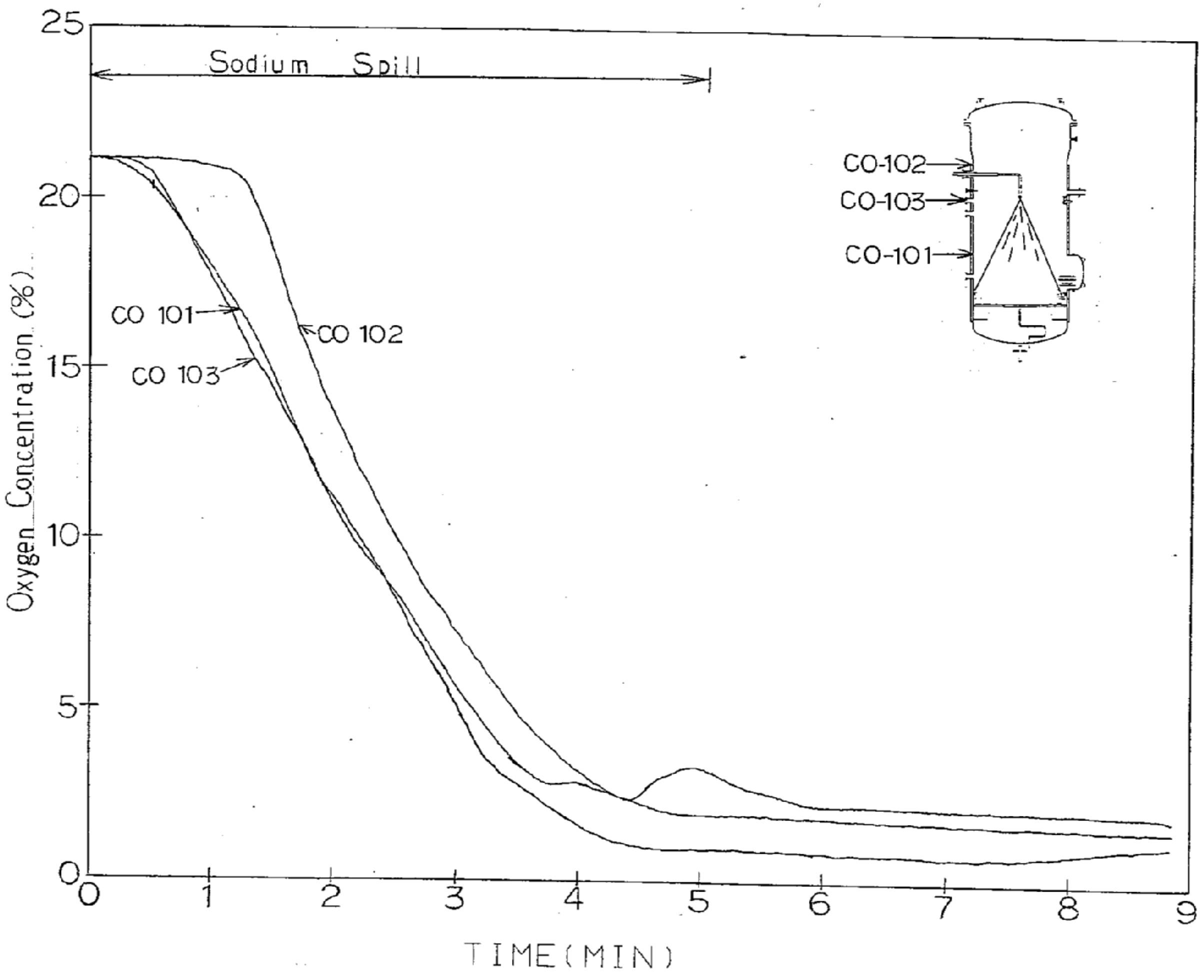
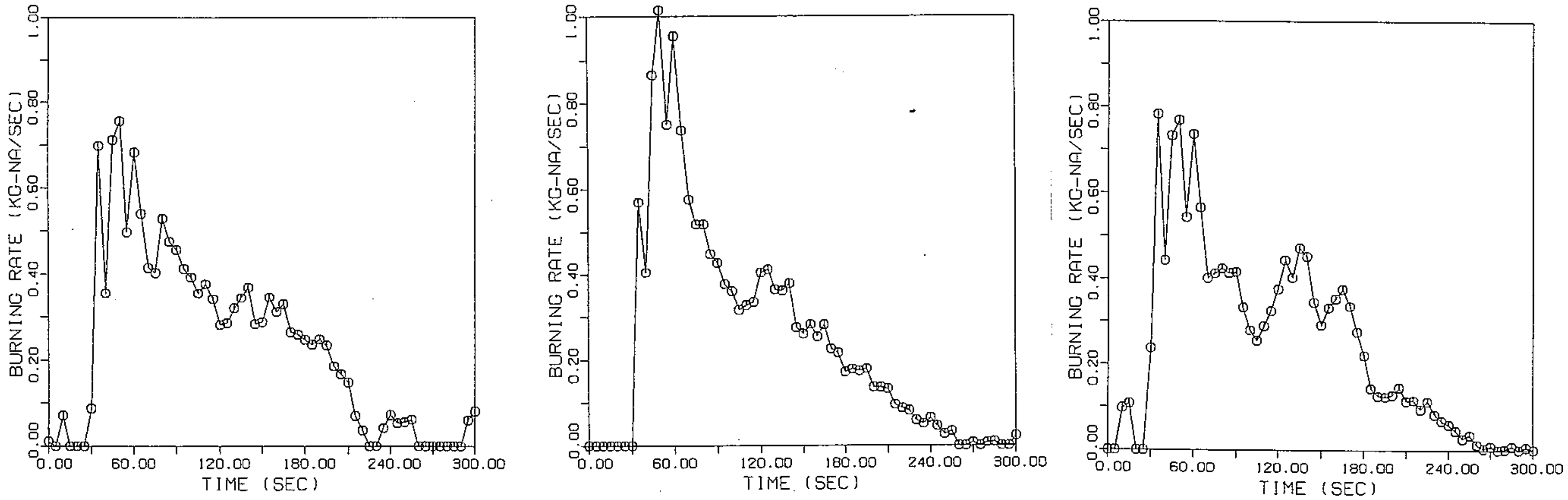


Fig. 13 Oxygen concentration in the vessel in air atmosphere test



CO-101　　　CO-102　　　CO-103

Fig. 14　Sodium burning rate estimated from oxygen concentration change in air atmosphere test

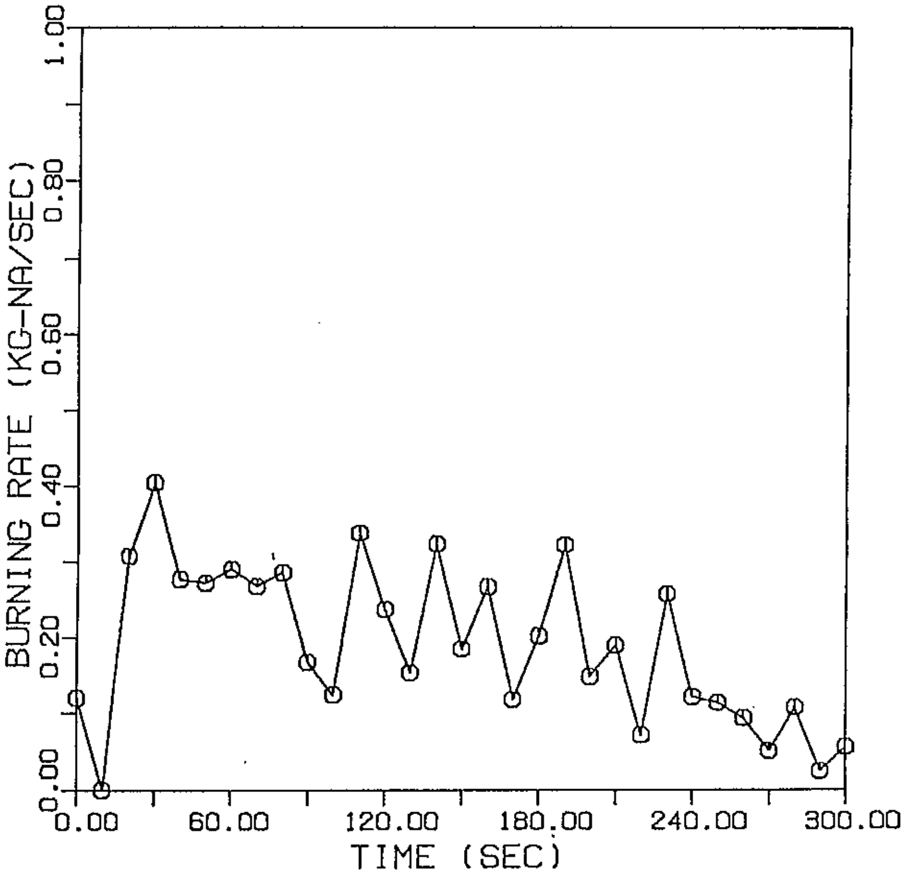


Fig. 15 Sodium burning rate estimated from temperature change in air atmosphere test

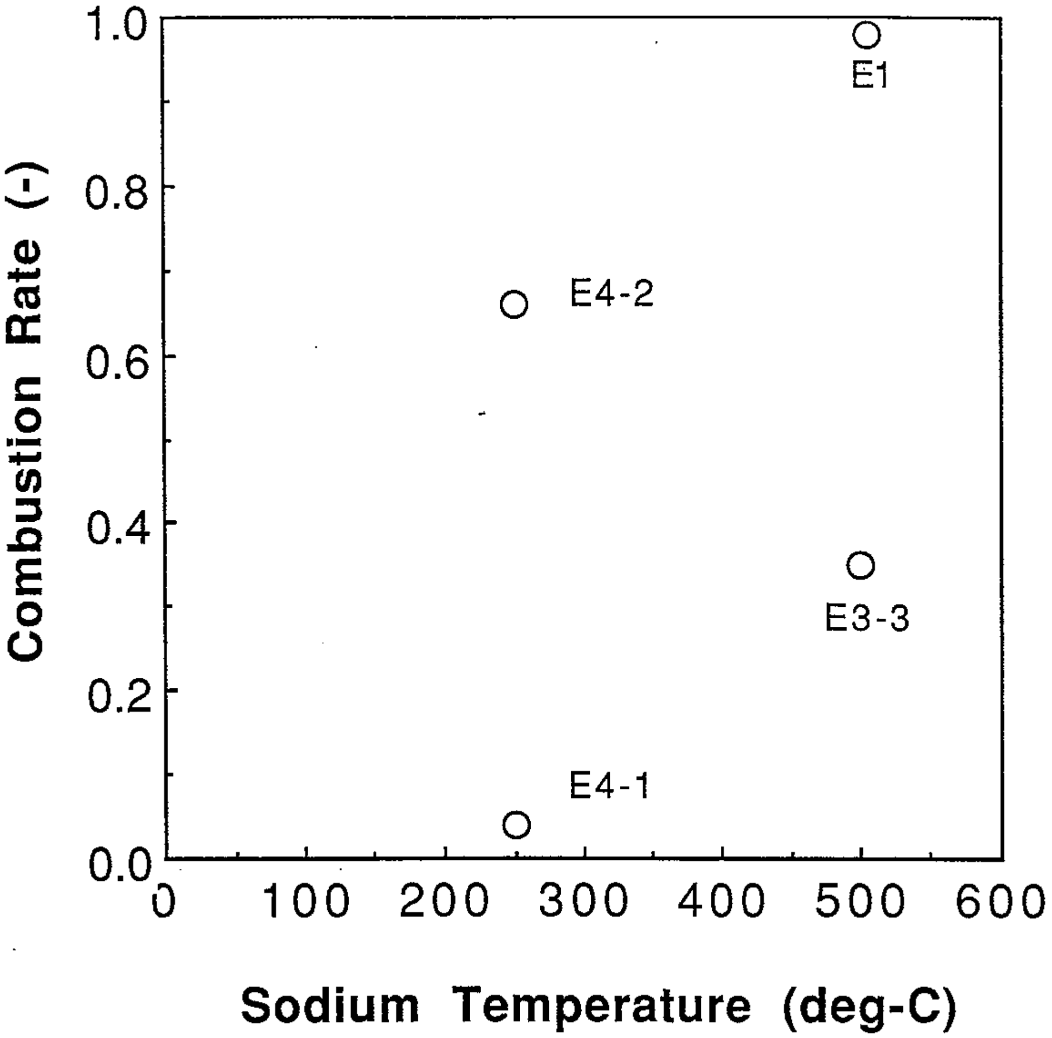


Fig. 16　Initial sodium temperature versus combustion rate

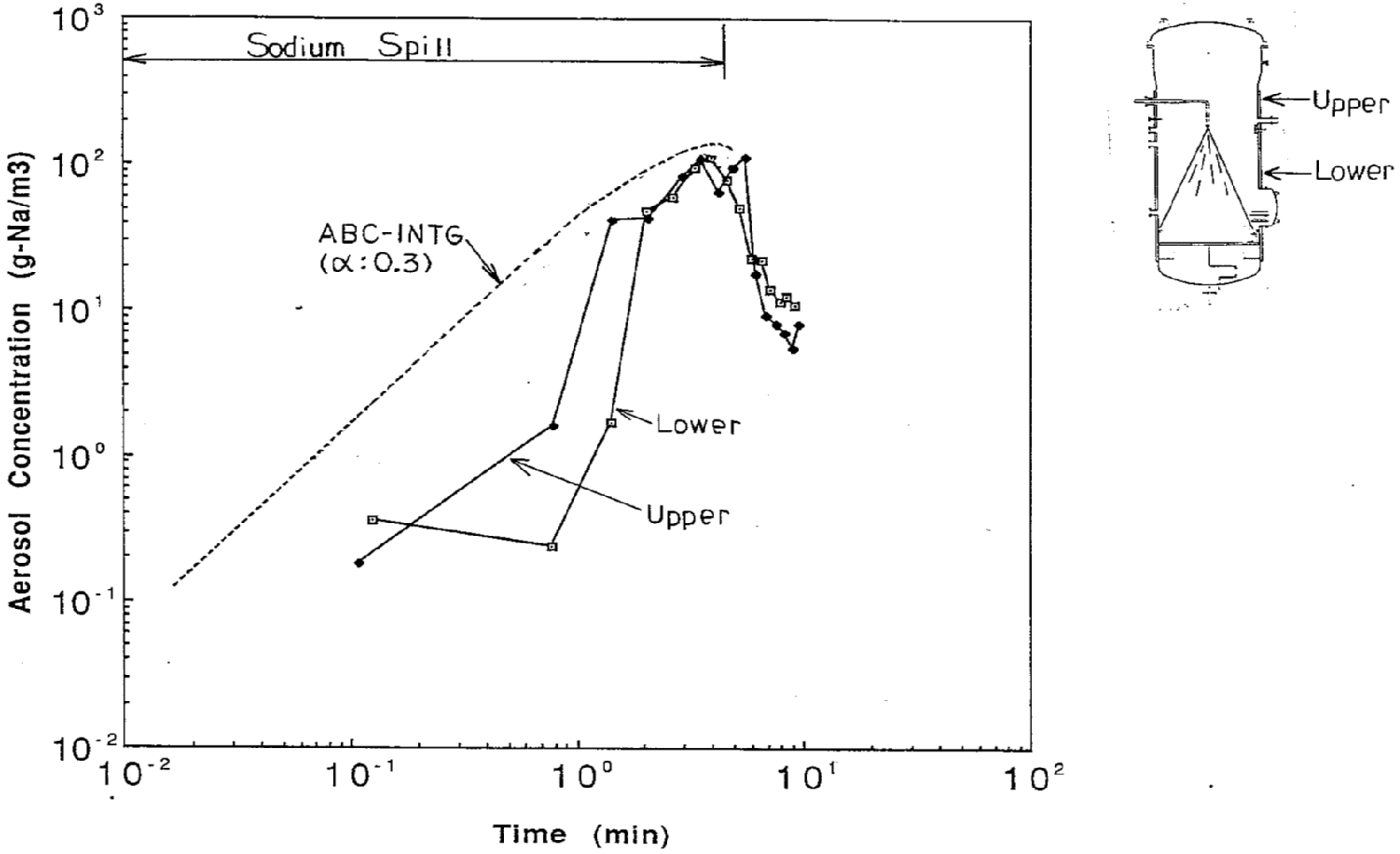


Fig. 17 Comparison of suspended aerosol concentration between test result and computation for air atmosphere test

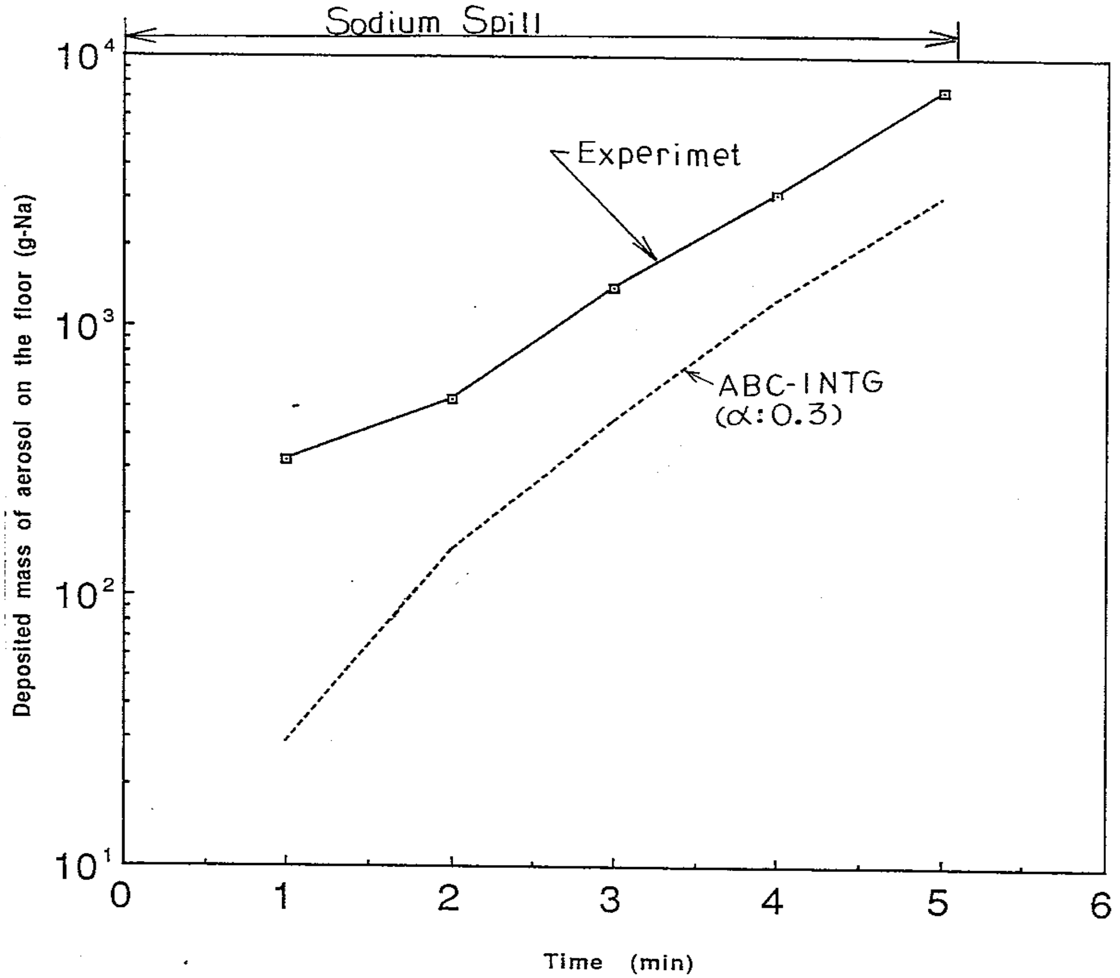


Fig. 18 Comparison of settled aerosol amount between test result and computation for air atmosphere test

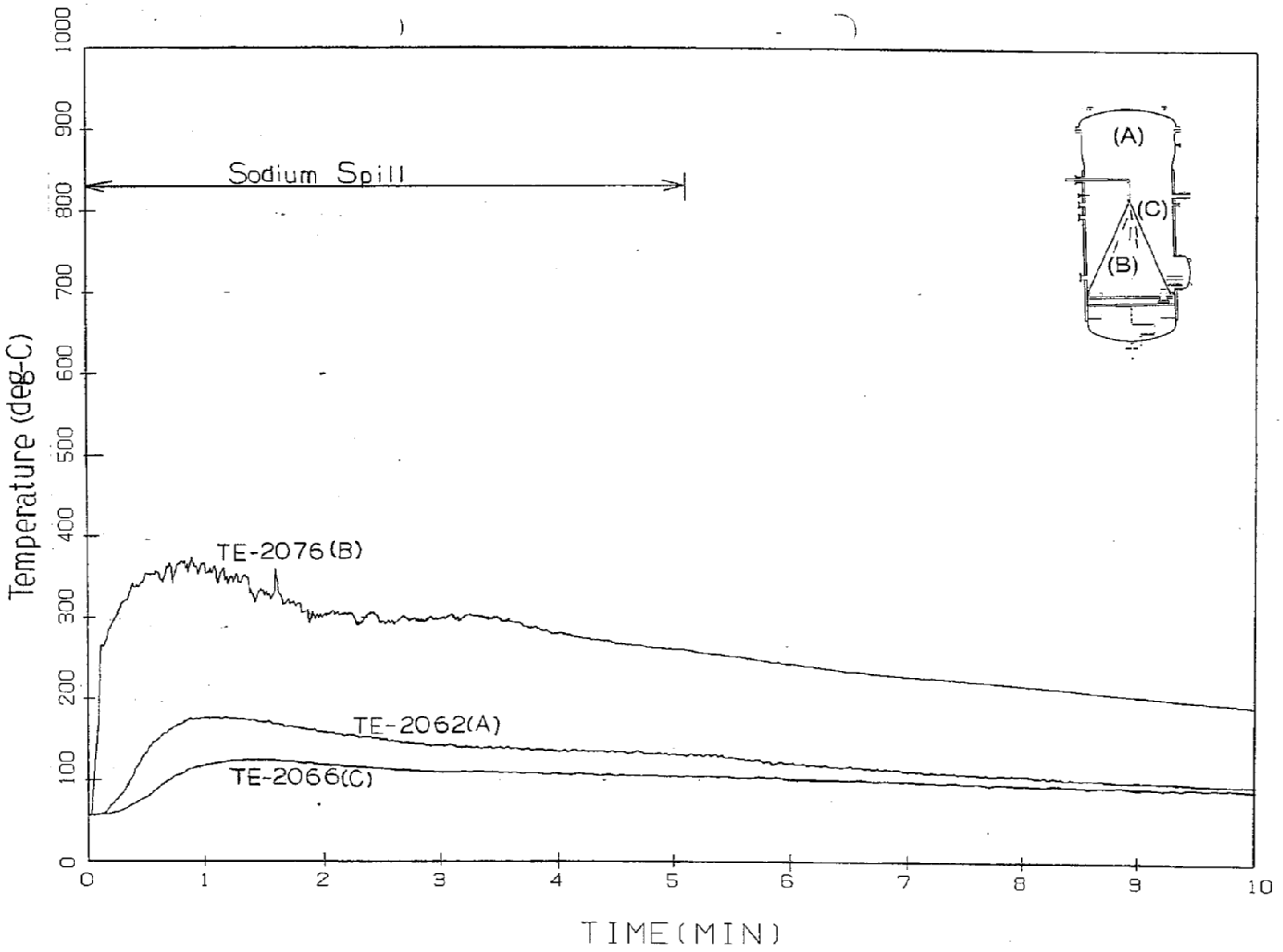


Fig. 19 Gas temperature in the vessel for low oxygen concentration test

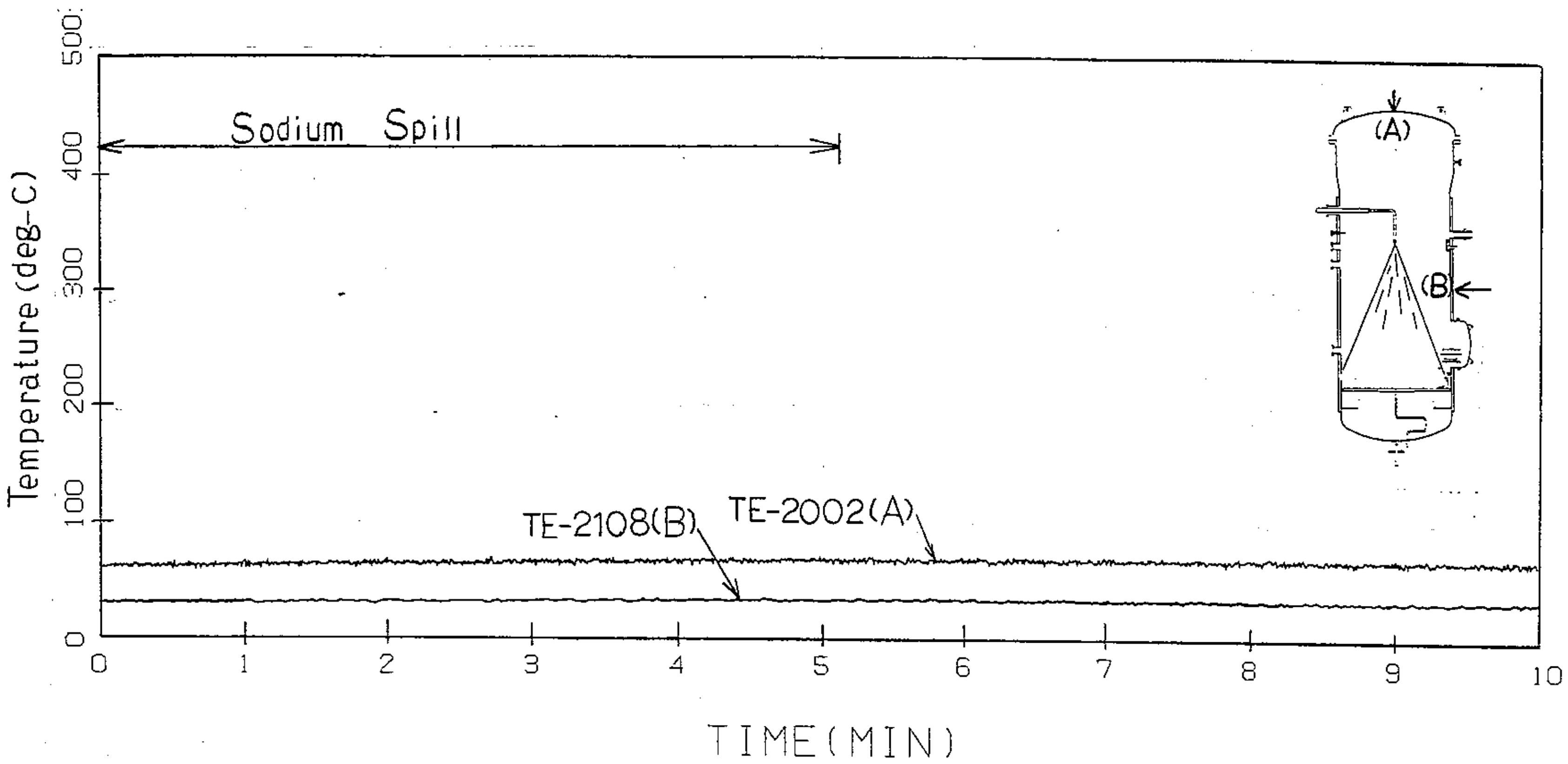


Fig. 20 Outer surface temperature of the vessel in low oxygen concentration test

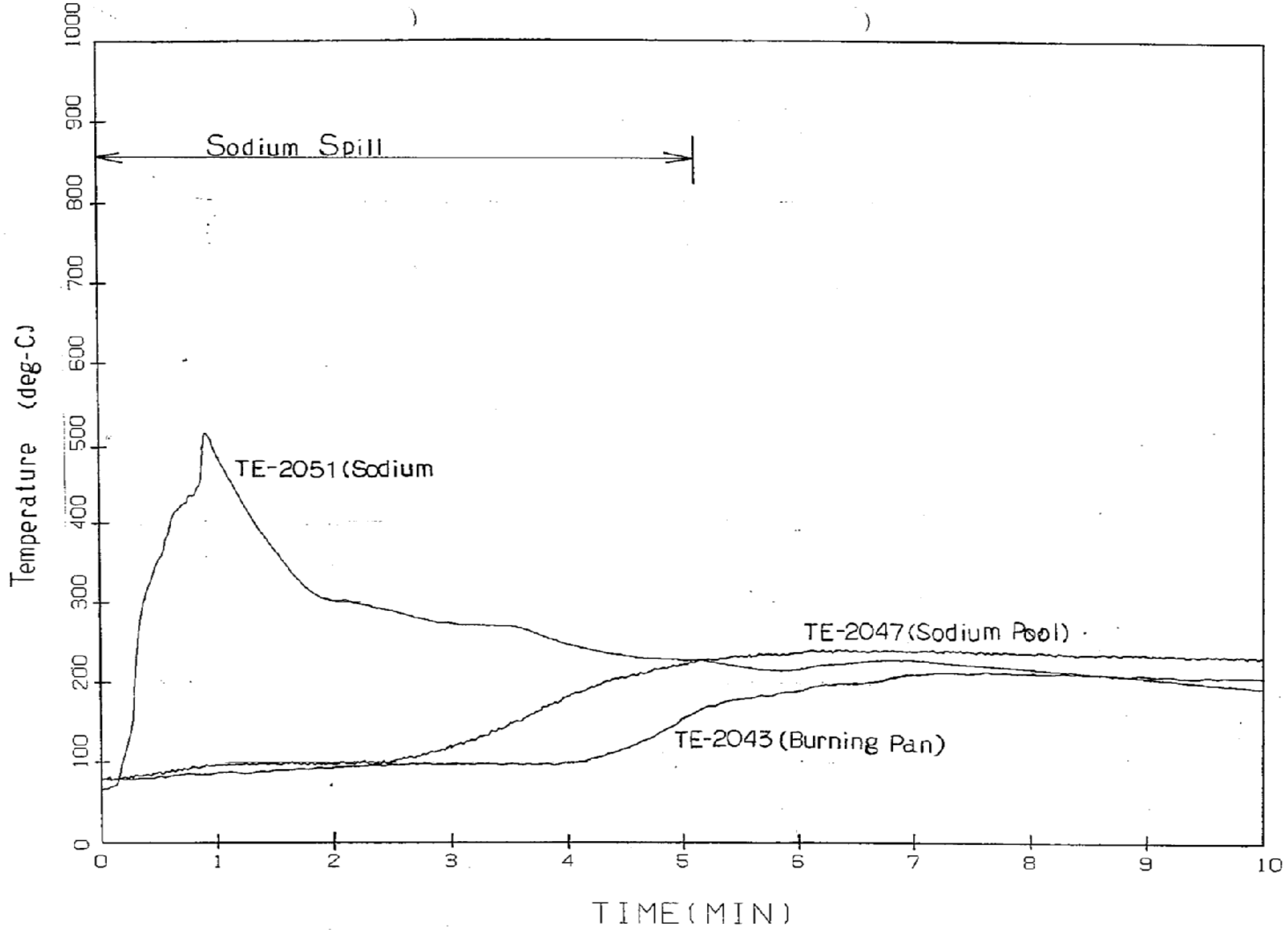


Fig. 21 Temperature of sodium catch pan and of sodium pool in low oxygen concentration test

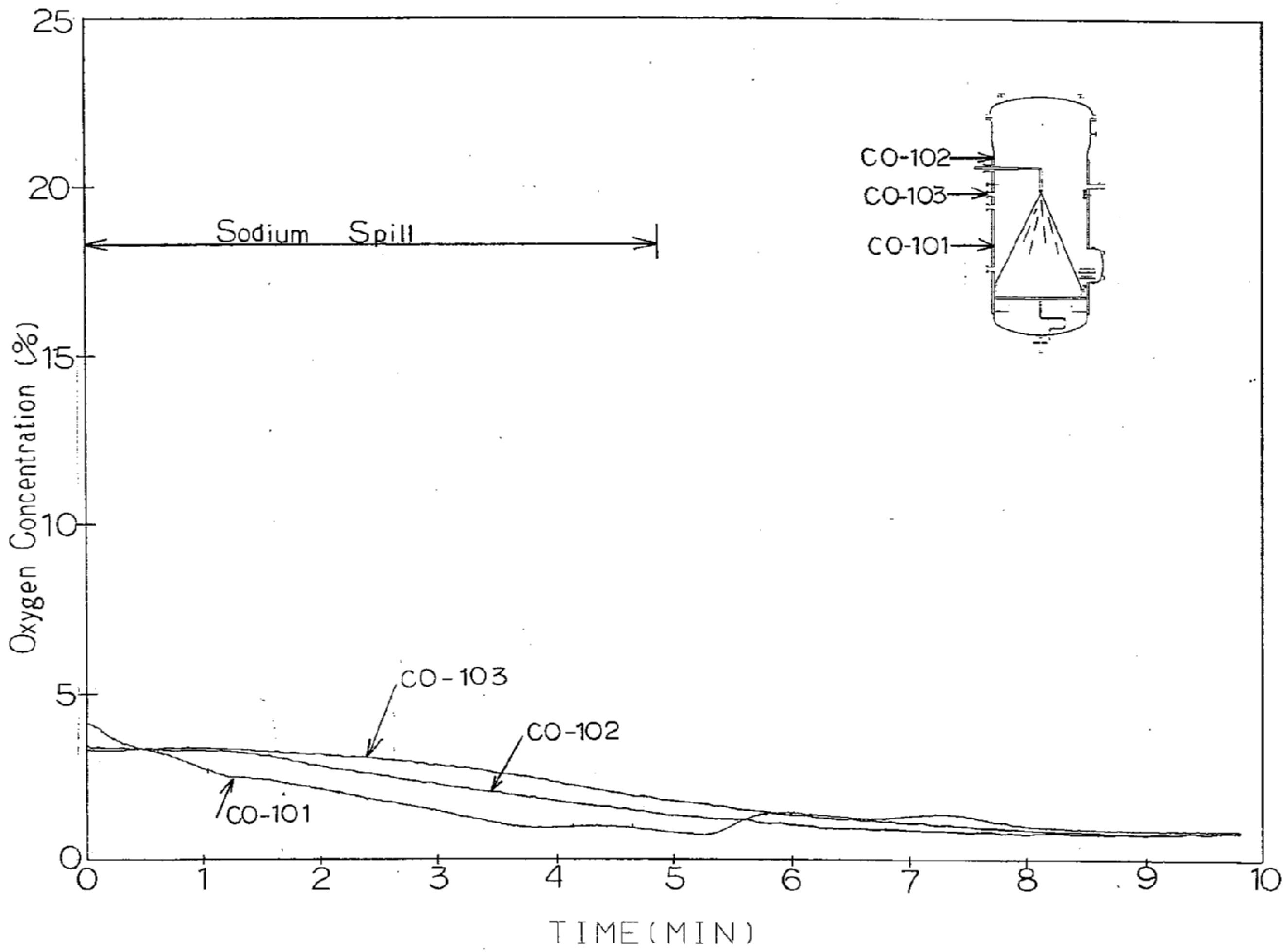


Fig. 22 Oxygen concentration in the vessel in low oxygen concentration test

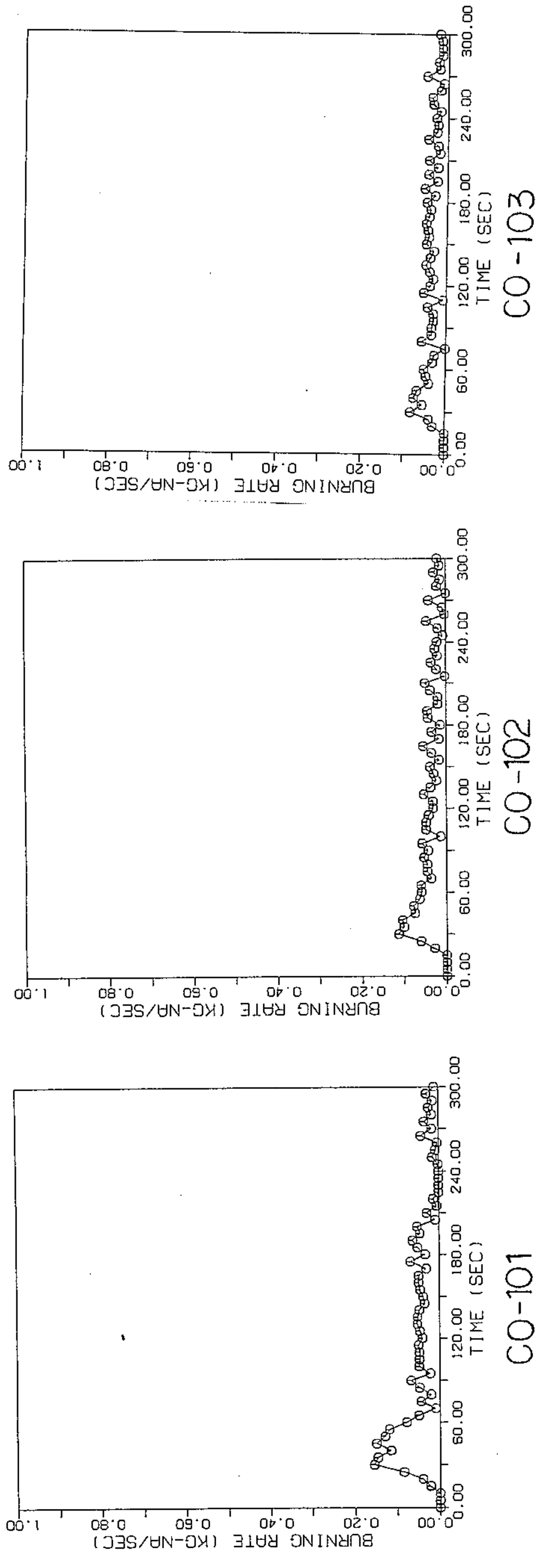


Fig. 23 Sodium burning rate estimated from oxygen concentration change in low oxygen concentration test

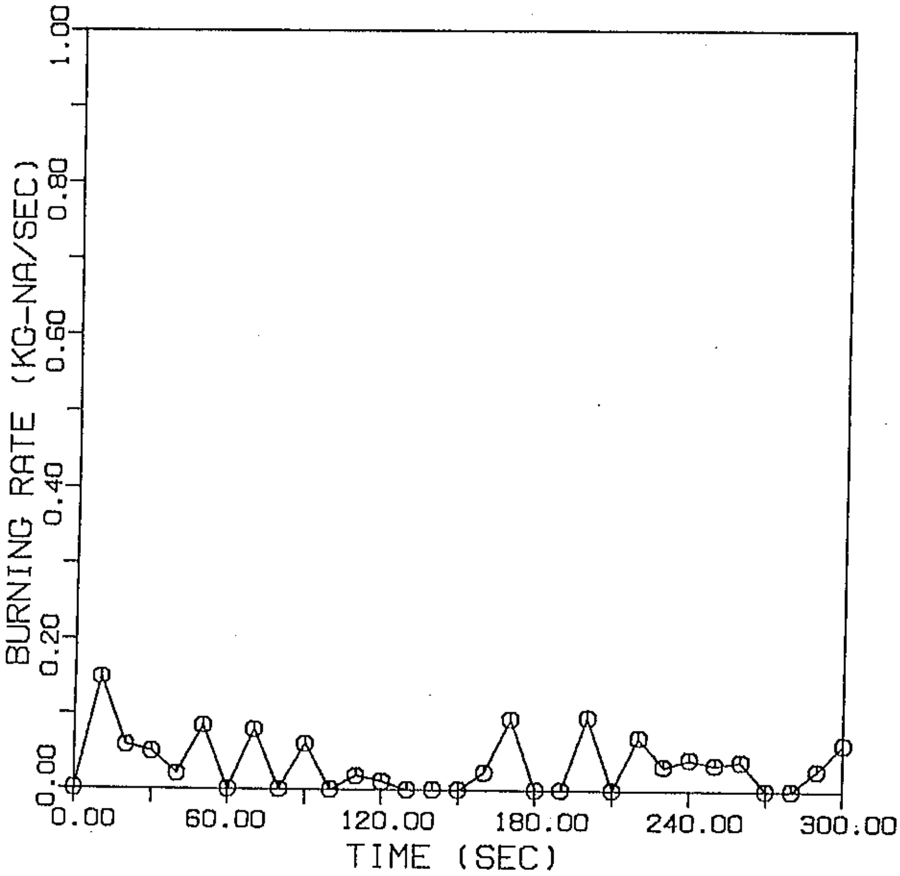


Fig. 24 Sodium burning rate estimated from temperature change in low oxygen concentration test

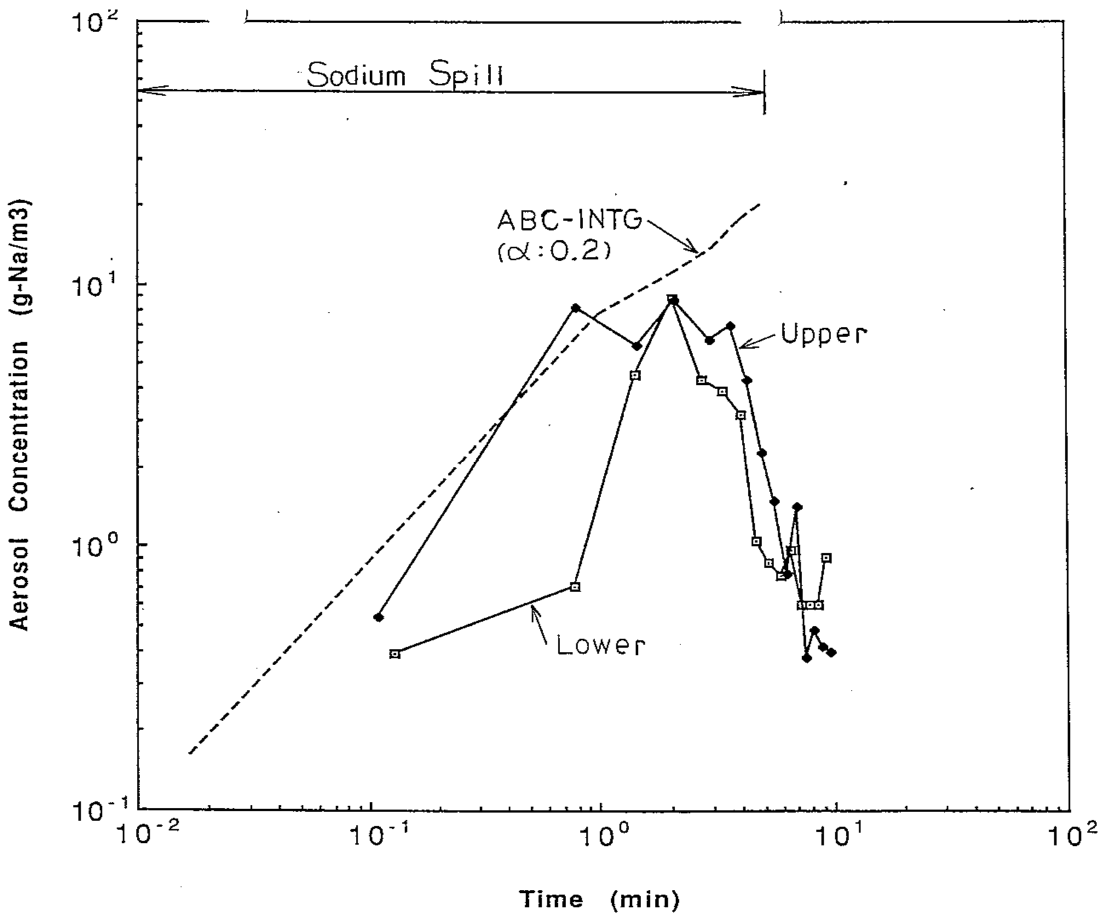


Fig. 25 Comparison of suspended aerosol concentration between test result and computation for low oxygen concentration test

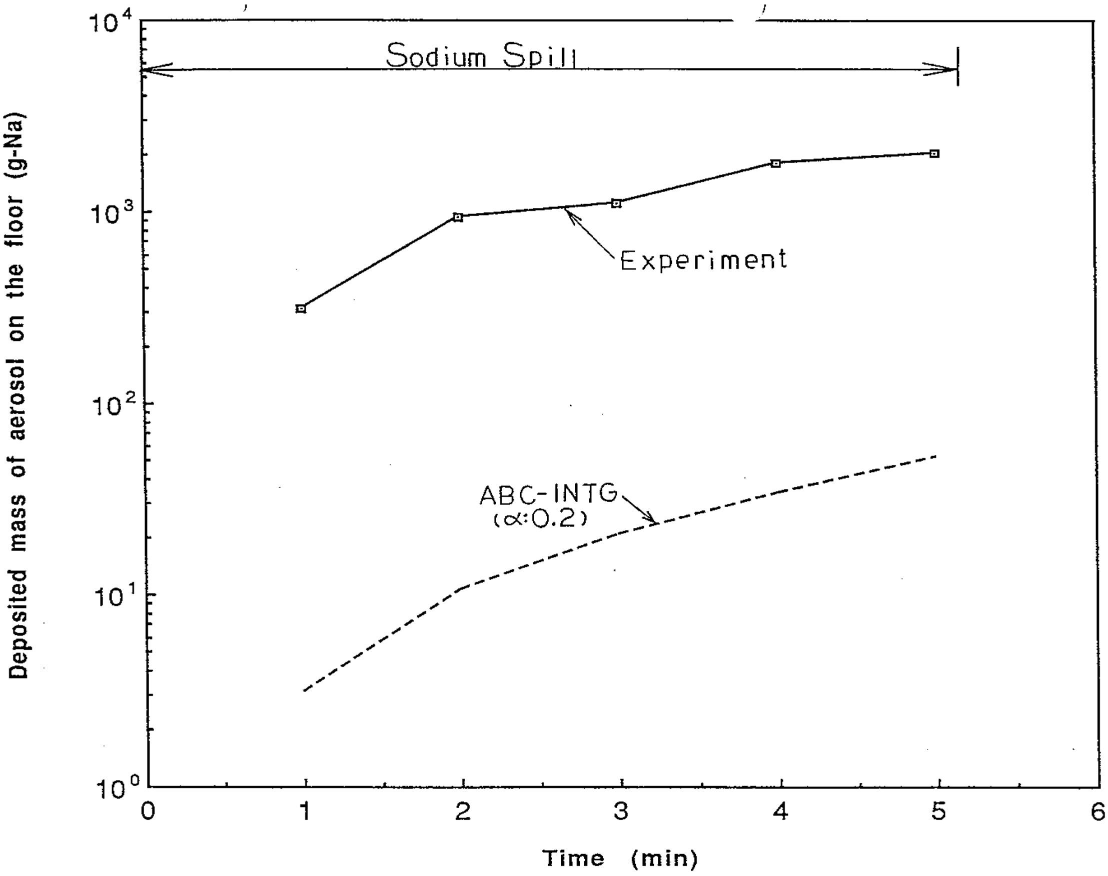


Fig. 26 Comparison of settled aerosol amount between test result and computation for low oxygen concentration test

国際単位系（SI）

表１．SI 基本単位

基本量	SI 基本単位	
	名称	記号
長さ	メートル	m
質量	キログラム	kg
時間	秒	s
電流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光度	カンデラ	cd

表２．基本単位を用いて表されるSI組立単位の例

組立量	SI 基本単位	
	名称	記号
面積	平方メートル	m^2
体積	立法メートル	m^3
速さ，速度	メートル毎秒	m/s
加速度	メートル毎秒毎秒	m/s^2
波数	毎メートル	m^{-1}
密度，質量密度	キログラム毎立方メートル	kg/m^3
面積密度	キログラム毎平方メートル	kg/m^2
比体積	立方メートル毎キログラム	m^3/kg
電流密度	アンペア毎平方メートル	A/m^2
磁界の強さ	アンペア毎メートル	A/m
量濃度(a)，濃度	モル毎立方メートル	mol/m^3
質量濃度	キログラム毎立法メートル	kg/m^3
輝度	カンデラ毎平方メートル	cd/m^2
屈折率(b)	（数字の） 1	1
比透磁率(b)	（数字の） 1	1

(a) 量濃度（amount concentration）は臨床化学の分野では物質濃度（substance concentration）ともよばれる。

(b) これらは無次元量あるいは次元１をもつ量であるが、そのことを表す単位記号である数字の１は通常は表記しない。

表３．固有の名称と記号で表されるSI組立単位

組立量	SI 組立単位			
	名称	記号	他のSI単位による表し方	SI基本単位による表し方
平面角	ラジアン(b)	rad	1 (b)	m/m
立体角	ステラジアン(b)	sr(c)	1 (b)	m$^{2/}$m^2
周波数	ヘルツ(d)	Hz		s^{-1}
力	ニュートン	N		m kg s^{-2}
圧力，応力	パスカル	Pa	N/m^2	m^{-1} kg s^{-2}
エネルギー，仕事，熱量	ジュール	J	N m	m^2 kg s^{-2}
仕事率，工率，放射束	ワット	W	J/s	m^2 kg s^{-3}
電荷，電気量	クーロン	C		s A
電位差（電圧），起電力	ボルト	V	W/A	m^2 kg s^{-3} A^{-1}
静電容量	ファラド	F	C/V	m^{-2} kg^{-1} s^4 A^2
電気抵抗	オーム	Ω	V/A	m^2 kg s^{-3} A^{-2}
コンダクタンス	ジーメンス	S	A/V	m^{-2} kg^{-1} s^3 A^2
磁束	ウエーバ	Wb	Vs	m^2 kg s^{-2} A^{-1}
磁束密度	テスラ	T	Wb/m^2	kg s^{-2} A^{-1}
インダクタンス	ヘンリー	H	Wb/A	m^2 kg s^{-2} A^{-2}
セルシウス温度	セルシウス度(e)	℃		K
光束	ルーメン	lm	cd sr(c)	cd
照度	ルクス	lx	lm/m^2	m^{-2} cd
放射性核種の放射能(f)	ベクレル(d)	Bq		s^{-1}
吸収線量, 比エネルギー分与, カーマ	グレイ	Gy	J/kg	m^2 s^{-2}
線量当量, 周辺線量当量, 方向性線量当量, 個人線量当量	シーベルト(g)	Sv	J/kg	m^2 s^{-2}
酸素活性	カタール	kat		s^{-1} mol

(a)SI接頭語は固有の名称と記号を持つ組立単位と組み合わせても使用できる。しかし接頭語を付した単位はもはやコヒーレントではない。

(b)ラジアンとステラジアンは数字の１に対する単位の特別な名称で、量についての情報をつたえるために使われる。実際には、使用する時には記号rad及びsrが用いられるが、習慣として組立単位としての記号である数字の１は明示されない。

(c)測光学ではステラジアンという名称と記号srを単位の表し方の中に、そのまま維持している。

(d)ヘルツは周期現象についてのみ、ベクレルは放射性核種の統計的過程についてのみ使用される。

(e)セルシウス度はケルビンの特別な名称で、セルシウス温度を表すために使用される。セルシウス度とケルビンの単位の大きさは同一である。したがって、温度差や温度間隔を表す数値はどちらの単位で表しても同じである。

(f)放射性核種の放射能（activity referred to a radionuclide）は、しばしば誤った用語で”radioactivity”と記される。

(g)単位シーベルト（PV,2002,70,205）についてはCIPM勧告2（CI-2002）を参照。

表４．単位の中に固有の名称と記号を含むSI組立単位の例

組立量	SI 組立単位		
	名称	記号	SI 基本単位による表し方
粘度	パスカル秒	Pa s	m^{-1} kg s^{-1}
力のモーメント	ニュートンメートル	N m	m^2 kg s^{-2}
表面張力	ニュートン毎メートル	N/m	kg s^{-2}
角速度	ラジアン毎秒	rad/s	m m^{-1} s^{-1}=s^{-1}
角加速度	ラジアン毎秒毎秒	rad/s^2	m m^{-1} s^{-2}=s^{-2}
熱流密度，放射照度	ワット毎平方メートル	W/m^2	kg s^{-3}
熱容量，エントロピー	ジュール毎ケルビン	J/K	m^2 kg s^{-2} K^{-1}
比熱容量，比エントロピー	ジュール毎キログラム毎ケルビン	J/(kg K)	m^2 s^{-2} K^{-1}
比エネルギー	ジュール毎キログラム	J/kg	m^2 s^{-2}
熱伝導率	ワット毎メートル毎ケルビン	W/(m K)	m kg s^{-3} K^{-1}
体積エネルギー	ジュール毎立方メートル	J/m^3	m^{-1} kg s^{-2}
電界の強さ	ボルト毎メートル	V/m	m kg s^{-3} A^{-1}
電荷密度	クーロン毎立方メートル	C/m^3	m^{-3} sA
表面電荷	クーロン毎平方メートル	C/m^2	m^{-2} sA
電束密度，電気変位	クーロン毎平方メートル	C/m^2	m^{-2} sA
誘電率	ファラド毎メートル	F/m	m^{-3} kg^{-1} s^4 A^2
透磁率	ヘンリー毎メートル	H/m	m kg s^{-2} A^{-2}
モルエネルギー	ジュール毎モル	J/mol	m^2 kg s^{-2} mol^{-1}
モルエントロピー, モル熱容量	ジュール毎モル毎ケルビン	J/(mol K)	m^2 kg s^{-2} K^{-1} mol^{-1}
照射線量（X線及びγ線）	クーロン毎キログラム	C/kg	kg^{-1} sA
吸収線量率	グレイ毎秒	Gy/s	m^2 s^{-3}
放射強度	ワット毎ステラジアン	W/sr	m^4 m^{-2} kg s^{-3}=m^2 kg s^{-3}
放射輝度	ワット毎平方メートル毎ステラジアン	W/(m^2 sr)	m^2 m^{-2} kg s^{-3}=kg s^{-3}
酵素活性濃度	カタール毎立方メートル	kat/m^3	m^{-3} s^{-1} mol

表５．SI 接頭語

乗数	接頭語	記号	乗数	接頭語	記号
10^{24}	ヨタ	Y	10^{-1}	デシ	d
10^{21}	ゼタ	Z	10^{-2}	センチ	c
10^{18}	エクサ	E	10^{-3}	ミリ	m
10^{15}	ペタ	P	10^{-6}	マイクロ	μ
10^{12}	テラ	T	10^{-9}	ナノ	n
10^9	ギガ	G	10^{-12}	ピコ	p
10^6	メガ	M	10^{-15}	フェムト	f
10^3	キロ	k	10^{-18}	アト	a
10^2	ヘクト	h	10^{-21}	ゼプト	z
10^1	デカ	da	10^{-24}	ヨクト	y

表６．SIに属さないが、SIと併用される単位

名称	記号	SI 単位による値
分	min	1 min=60s
時	h	1h =60 min=3600 s
日	d	1 d=24 h=86 400 s
度	°	1°=(π/180) rad
分	’	1’=(1/60)°=(π/10800) rad
秒	”	1”=(1/60)’=(π/648000) rad
ヘクタール	ha	1ha=1hm^2=10^{4}m^2
リットル	L，l	1L=1l=1dm^3=10^{3}cm^3=10^{-3}m^3
トン	t	1t=10^3 kg

表７．SIに属さないが、SIと併用される単位で、SI単位で表される数値が実験的に得られるもの

名称	記号	SI 単位で表される数値
電子ボルト	eV	1eV=1.602 176 53(14)×10^{-19}J
ダルトン	Da	1Da=1.660 538 86(28)×10^{-27}kg
統一原子質量単位	u	1u=1 Da
天文単位	ua	1ua=1.495 978 706 91(6)×10^{11}m

表８．SIに属さないが、SIと併用されるその他の単位

名称	記号	SI 単位で表される数値
バール	bar	1 bar=0.1MPa=100kPa=10^{5}Pa
水銀柱ミリメートル	mmHg	1mmHg=133.322Pa
オングストローム	Å	1 Å=0.1nm=100pm=10^{-10}m
海里	M	1 M=1852m
バーン	b	1 b=100fm^2=(10^{-12}cm)2=10^{-28}m^2
ノット	kn	1 kn=(1852/3600)m/s
ネーパ	Np	SI単位との数値的な関係は、対数量の定義に依存。
ベル	B	
デジベル	dB	

表９．固有の名称をもつCGS組立単位

名称	記号	SI 単位で表される数値
エルグ	erg	1 erg=10^{-7} J
ダイン	dyn	1 dyn=10^{-5}N
ポアズ	P	1 P=1 dyn s cm^{-2}=0.1Pa s
ストークス	St	1 St =1cm^2 s^{-1}=10^{-4}m^2 s^{-1}
スチルブ	sb	1 sb =1cd cm^{-2}=10^{4}cd m^{-2}
フォト	ph	1 ph=1cd sr cm^{-2} 10^{4}lx
ガル	Gal	1 Gal =1cm s^{-2}=10^{-2}ms^{-2}
マクスウェル	Mx	1 Mx = 1G cm^2=10^{-8}Wb
ガウス	G	1 G =1Mx cm^{-2} =10^{-4}T
エルステッド(c)	Oe	1 Oe ≙ (10^3/4π)A m^{-1}

(c) ３元系のCGS単位系とSIでは直接比較できないため、等号「 ≙ 」は対応関係を示すものである。

表10．SIに属さないその他の単位の例

名称	記号	SI 単位で表される数値
キュリー	Ci	1 Ci=3.7×10^{10}Bq
レントゲン	R	1 R = 2.58×10^{-4}C/kg
ラド	rad	1 rad=1cGy=10^{-2}Gy
レム	rem	1 rem=1 cSv=10^{-2}Sv
ガンマ	γ	1 γ =1 nT=10-9T
フェルミ		1フェルミ=1 fm=10-15m
メートル系カラット		1メートル系カラット = 200 mg = 2×10-4kg
トル	Torr	1 Torr = (101 325/760) Pa
標準大気圧	atm	1 atm = 101 325 Pa
カロリー	cal	1cal=4.1858J（「15℃」カロリー），4.1868J（「IT」カロリー）4.184J（「熱化学」カロリー）
ミクロン	μ	1 μ =1μm=10^{-6}m

（第8版，2006年改訂）