Development and Demonstration of Sodium Fire Mitigation System in the SAPFIRE Facility

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Abstract

Flow pattern of a realistic sodium leak from the sodium piping equipped with jackets and thermal insulator was experimentally investigated. Then, based on this result, the fire mitigation system consisting of an inclined liner, a drain piping, and a smothering tank has been developed.The performance of the system was, in final, validated in the large-scale sodium leak and fire test in the SAPFIRE facility.

1. Introduction

In the secondary system of the liquid sodium cooled fast breeder reactors, a sodium leak from the piping is postulated as the design basis accident. Size of the leak hole for such an accident is given by LBB (the leak before break theory). Theoretical background of LBB is up-dating by taking into account the recent advance in fracture mechanics. However, the area so far given is one-quarter Dt, where D is the pipe diameter and t is the pipe wall thickness, which leads to a comparatively large sodium leak with flow rate of several tens of kilograms per second. Such a large sodium leak in an air atmosphere of the reactor auxiliary building may generate a large combustion heat as well as a large masses of sodium aerosols.

To mitigate the consequences of the accident, the mitigation system has been developed and its performance was validated. In the development, a leak flow pattern for a piping and associated combustion were investigated at first. In next, a reduced scale model of the system to be installed in the reactor was developed, and its validation test was conducted. In final, consequence of sodium aerosol deposits on the electrical instruments and the reactor key components was tested.

2. Leakage Flow Pattern from Sodium Piping

In the safety evaluation of the design-basis sodium leak accident, a spray fire has been postulated. Usually, a spray fire gives the largest possible combustion heat, therefore, it gives the most pessimistic consequences. However, the relation between a realistic leak and a postulated spray has not yet been studied.

To investigate a real flow pattern and associated combustion during a leak, water and sodium tests have been conducted using a full size mock-up and a reduced scale model of the secondary sodium piping of the reactor plant, respectively.

(1) Water Simulation Test

Full size mockups of the prototype sodium pipings (straight pipe, T-pipe, and L-pipe) equipped with the inner jackets, the thermal insulators, and the outer jackets were used for the test. Figure 1 shows the straight pipe for illustration. They were mounted one by one in a water test loop, whose arrangement is shown in Fig.2. In each of the pipe, a leak hole was drilled in its wall. Water pressure at the rated flow conditions of the reactor secondary system was added to the pipe, then the leak flow pattern was visually observed. The results indicated that no spray was fromed, instead, only a disperse flow through the gaps of the outer jacket was generated. Since generating of droplets could not be suppressed effectively, the outer jacket was remodeled based on the test results.

(2) Sodium Leak Test

The remodeled piping was sodium tested. A 1/8 scale model of the piping was manufactured for this purpose and was installed in the stainless steel vessel, SOLFA- 2, in the SAPFIRE facility. SAPFIRE is a large scale sodium leak, fire, and aerosols test facility constructed in 1985, whose bird's-eye view is shown in Fig.3. It consists of three test rigs; SOLFA-1 (two storied concrete cell), SOLFA-2, and FRAT-1 (small stainless steel vessel). SOLFA-2 is 10 m in height, 3.4 m in diameter, and 200 m^3 in inner volume. In the present test, distance between the pipe and a floor in SOLFA-2 was 2.5 m.

In the leak test, a 2.4 tons of sodium at 505°C was fed to the test pipe at a flow rate of 3.1 kg/sec for 13 minutes. During the leak, pictures of a leakage flow were taken by a video camera and an infrared camera. In addition, an extent of a leakage flow and the spatial temperature distribution during a leak were measured by the more than 200 thermocouples arranged horizontally and vertically between the test pipe and the floor.

Pictures taken by the cameras showed that the flow pattern is a downward column along which no marked ignition occurred. Only the rebound droplets from the floor ignited and burnt. This flow pattern was also made sure by the transient spatial temperature distributions, as shown in Fig.4. Fraction of a leakage sodium burnt during the test was 4 %, while that fraction ranged 30% in another spray fire test.

Post-test examination of the piping revealed no failure of the jackets and no burning of the thermal insulator around the pipe.

3. Development and Validation of Fire Mitigation System

(1) Small Scale Model

Small scale models of the components for the mitigation system; the liner, the drain piping, and the smothering tank, were developed based on the above results, then their performances were studied in the sodium test.

For the liner and the drain pipe, transient thermal responses including thermal deformations and heat transfer rates from a hot sodium to the components were measured. For the smothering tank, apparent combustion rate of sodium was determined. Results is shown in Fig.5, where the left hand side shows the combustion rate with open pool and the right hand side shows that in the smothering tank with its opening ratio at 1%. The combustion rate with the reduced opening ratio is seen to be less than a few percent of that with the open pool.

These components were assembled into a mitigation system, and its performance was tested using a 180 kg sodium at 500°C. The system functioned properly.

(2) Prototype System

Prototype mitigation system was developed based on the above results. It was mounted in the two-storied concrete test rig, SOLFA-1, whose test arrangement is shown in Fig.6. In the upper cell, the similar 1/8 reduced scale model of the sodium piping as described was installed above 2.0 m from the floor liner, and a catch-pan type inclined floor liner were installed on its floor. The smothering tank was mounted in its lower cell. The smothering tank and the liner was connected by a drain piping.

In the test, a 3 tons of sodium heated up to 505°C was spilled from the pipe at a flow rate of 3.2 kg/sec for 15 minutes. Then, the sodium was allowed to burn on the liner or in the smothering tank for 6.6 hours. During that time, atmospheric oxygen concentrations in the upper and lower cells were kept nearly 21 % by feeding oxygen gas or by ventilation.

The similar column flow as observed in SOLFA-2 was also obtained with the leak from the piping. The maximum aerosol concentration determined was 23 g/m^3 in the upper cell. Figure 7 shows the combustion rate in the upper cell during and after the sodium spill. As can be seen in the figure, the combustion rate due to mixed fires (rebound droplets and pool) was from 100 to 130 kW/m^2 of floor liner that is only 1.1 to 1.3 times larger than that of a pool fire (100 kW/m^2). The combustion rate decreased gradually after the sodium leak because of the smooth draining of sodium in the smothering tank. In the smothering tank, a combustion of the drained sodium was self-extinguished after several tens of minutes due to quick consumption of oxygen in the tank, as shown in Fig.8. It is seen that combustion rate decreased significantly from 50 kW/m^2 to less than 5 kW/m^2 within several tens of minutes. Due to the effective self-extinguishment in the smothering tank as presented, the temperature of drained sodium dropped monotonously, as shown in Fig.9, where the calculated result by the ASSCOPS code is also drawn by a solid line. Agreement between the code and the test results is fairly well. During the test, only small amount of aerosol was released into the lower cell, thus the maximum aerosol concentration was only 5 g/m^3.

In the post-test examination, sodium and combustion products at various locations in the test facility were recovered, and their weights were measured. The results are shown in Fig.10. More than 90 % of a spilled sodium is seen to be recovered in the smothering tank. The rest changed to aerosols, and they deposited on the floors, walls, and ceilings and released to the scrubber.

The conclusion from the present tests is that the system developed functioned properly. It recovered a spilled sodium effectively and extinguished its fire without generating excess combustion heat and sodium aerosols.

(3) Evaluation of Temperatures of Steel Lined Concrete

Since integrity of structural concrete during a sodium leak accident is another important issue, thermal conduction of a steel lined concrete has been studied. Figure 11 shows the test section. Gas burners are mounted at the top of the test section to simulate heating of the steel lined concrete surface by a combustion or a spilled sodium. Between the steel liner and the upper concrete surface, perlite concrete is filled. Since heated perlite and structural concrets release water vapor, a steam vent line is provided. In parallel to this test, thermo-physical properties of the components of steel lined structural concrete were determined from room temperature to 500°C. Then, thermal conduction of the test section was analyzed by the multi-dimensional thermal conduction code, FINAS, using the results obtained.

The results of vertical temperature profile and its change are shown in Fig.12. The solid lines represent the test results and the dotted lines represent the calculated results. It is seen that agreement between the code and the test is comparatively well. Results of the analysis indicated that the concrete surface was well thermally insulated by perlite, thus, it was not heated up higher than about 80°C throughout the test. In conclusion, integrity of the structural concrete can be kept even in the sodium leak accident conditions.

4. Consequence of Sodium Aerosol Deposition on Components

Following a sodium fire, sodium aerosols such as sodium oxide, sodium peroxide, and sodium hydroxide are generated. These combustion products are chemically reactive, therefore, their deposition on the electrical instruments may cause problems. In addition, released aerosol may be taken into an air cooler that is under operation for decay heat removal and may cause a decrease in its heat exchanging capacity.

To evaluate such possible problems, the aerosol exposure tests were carried out for the key electrical and the reactor components. Highlights of the results are presented in another paper of this meeting, which shows that, except a few, no serious problem was experienced for the electrical instruments, valves, and pony motor for mechanical pump. In this paper, the test for an air cooler will be presented hereafter.

Figure 13 shows an arrangement of the test rig for the air cooler. The rig is consisted of an aerosol generator, a mixing chamber, a test air cooler, and a water scrubber. They are connected in series in an air duct. The test air cooler is a partial full size mockup of a real cooler and is consisting of six heater tubes and eight non-heat-generating dummy tubes. All of the tubes are finned type.

In the test, sodium aerosol from the aerosol generator was forced flowed through the air duct for 24 hours at the aerosol concentration of 0.1 g/m^3. Changes in apparent heat transfer coefficients between the heater tubes and the flowing air were continuously monitored by measuring the temperature differences between the tubes and the flowing air. Figure 14 shows the results. A relationship between the decrease in average heat transfer coefficient and the average weight of aerosol deposits on the single tube is plotted. It is seen that the decreasing rate is saturated at larger deposits weight than about 50 g/tube. From the results of the post-test inspection of the cooler, this saturation was attributed to the fact that deposition occurred due to impaction, therefore, aerosols deposited mainly on the up-stream side surface of the tubes, as shown in Photo.1.

4.Conclusions

1)To suppress generating the sodium droplets during a leak, structure of the sodium piping was remodeled. Sodium test results with the remodeled piping indicated that flow pattern of a leakage sodium is a downward column that generates smaller combustion heat than a spray.

2) Fire mitigation system consisting of an inclined catch-pan type floor liner, a drain piping, and a smothering tank was developed through a series of development test. Result of sodium test for the system clearly indicated that a spilled sodium is recovered smoothly and its fire is extinguished effectively without generating of excess heat and aerosol. Procedure to evaluate thermal conduction of the concrete during a sodium spill was established and validated by the test.

3) Consequences of sodium aerosol deposition on the key electrical and the reactor components showed no serious problems. Decreasing in heat exchanging capacity of an air cooler with aerosol containing air was investigated. Then a relationship between the decrease of heat transfer cefficient and the deposits weight on the finned tubes was obtained.

Acknowledgment

The authors express their deep gratitude to Merrs.T.Fukuchi and K.Kawata, Plant Safety Engineering Section, OEC, PNC for their technical assistance in conduction the tests and in making analysis of the test results.

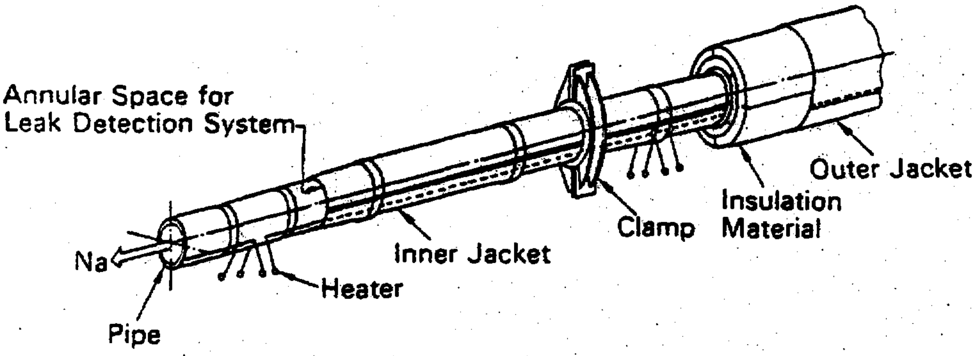

Fig. 1 Concept of Secondary Sodium Piping

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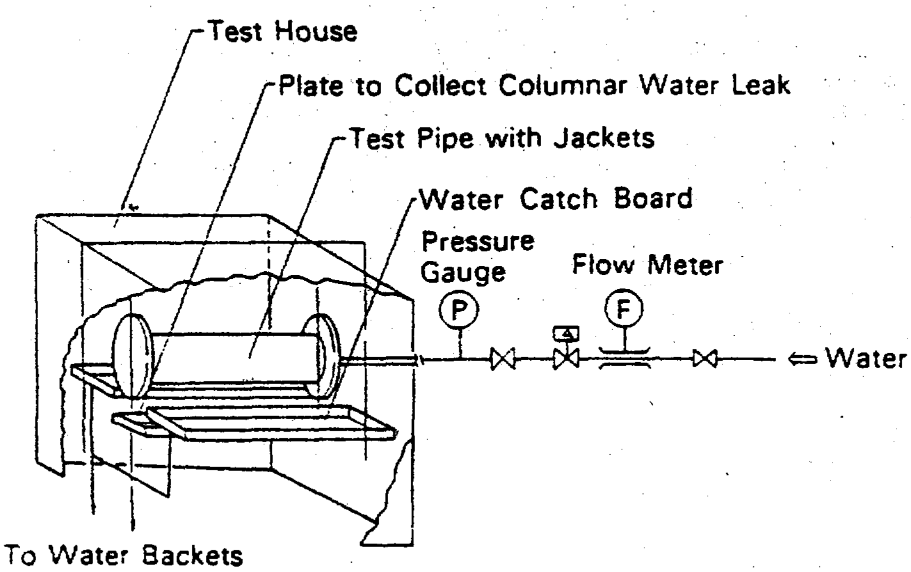

Fig. 2 Flow Sheet of Water Test Loop

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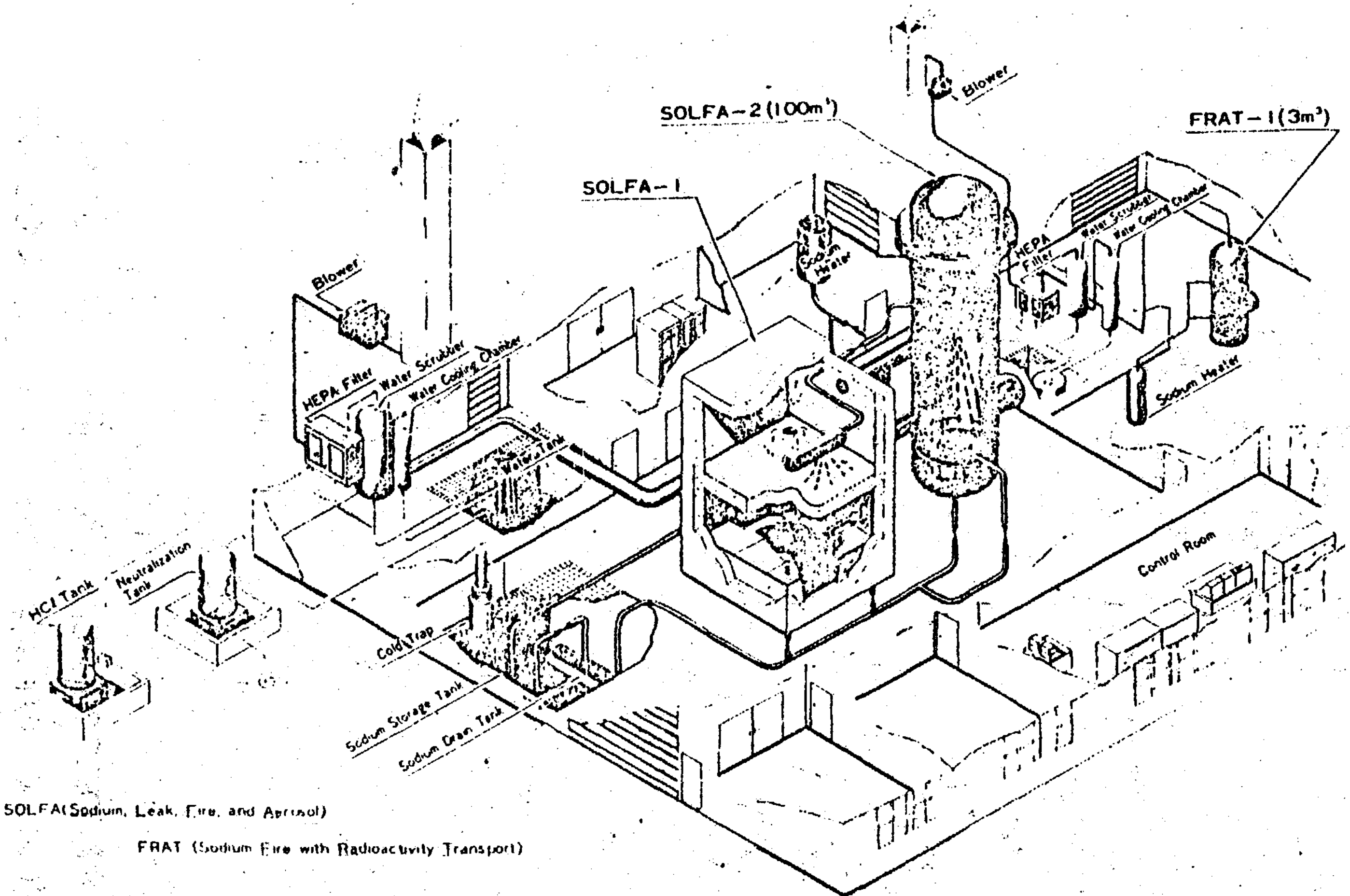

Fig. 3 Bird's-eye View of SAPFIRE Facility

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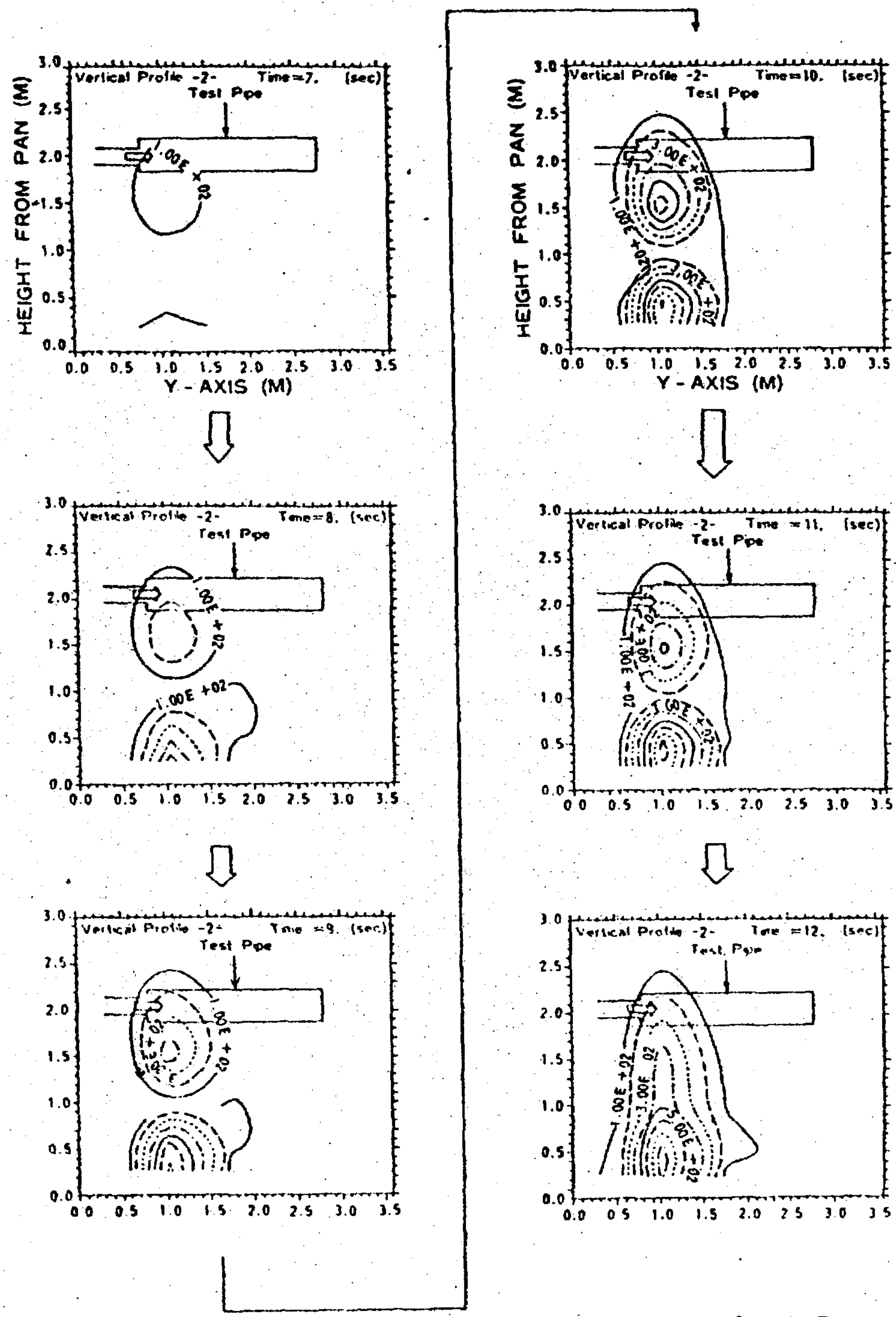

Fig. 4 Temperature Profiles in Gas Phase below Simulated Sodium Pipe (Vertical Profiles)

(PSS - SFE 394)

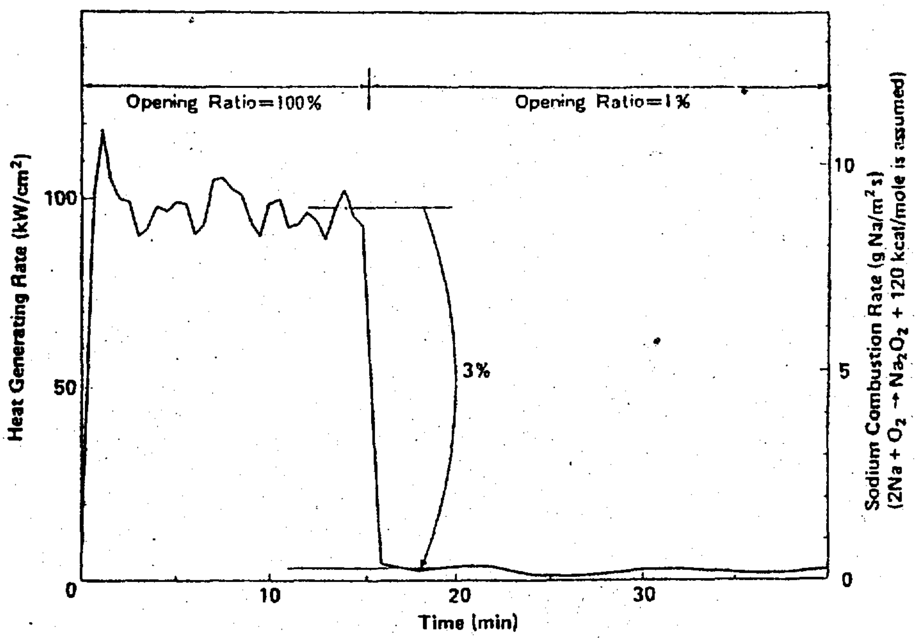

Fig. 5 Comparison of Heat Generation Rates with Open Pool Combustion and with Slit Board Combustion

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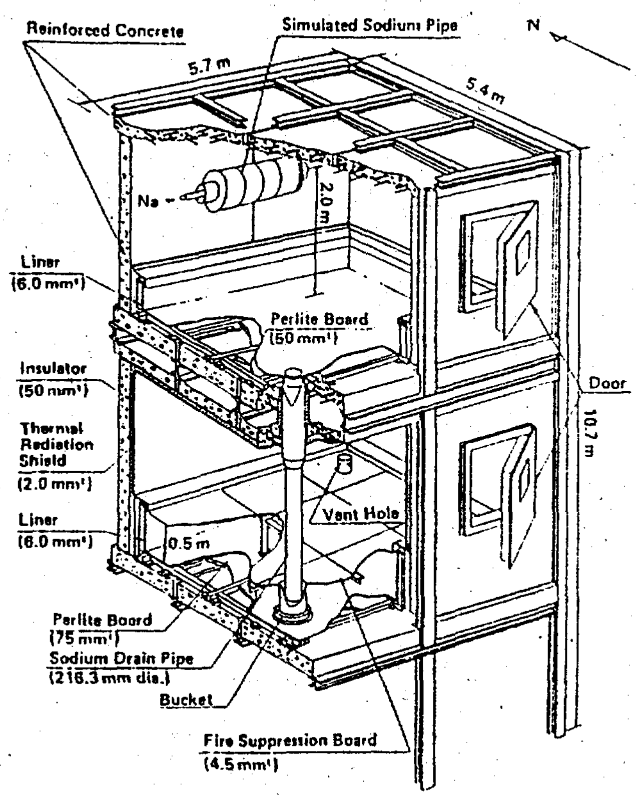

Fig. 6 Bird's-eye View of SOLFA-1 for Run-D2

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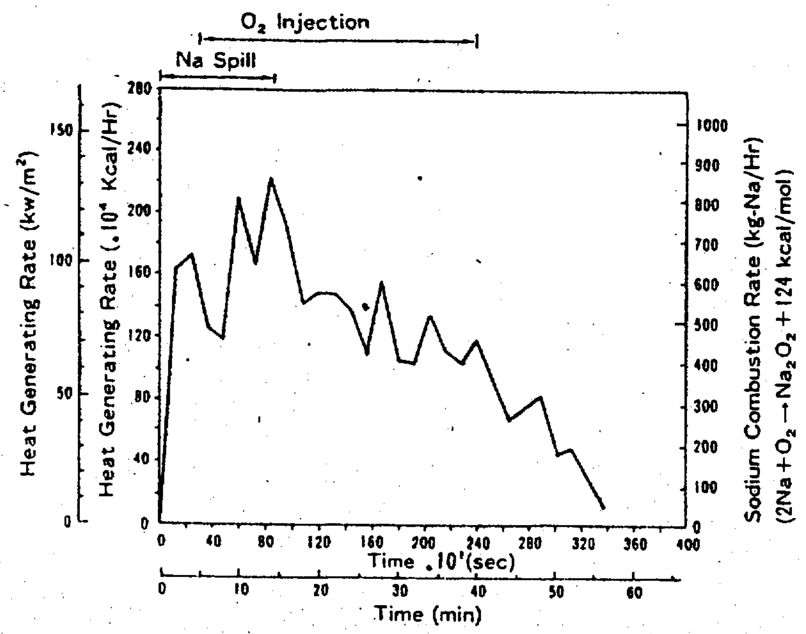

Fig. 7 Heat Generating Rate and Sodium Combustion Rate during the Test (Upper Cell)

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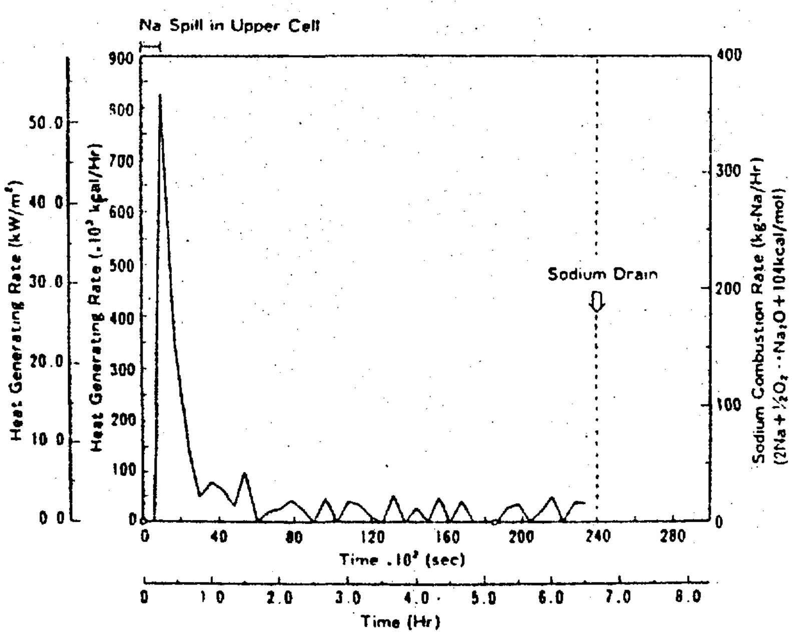

Fig. 8 Heat Generating Rate and Sodium Combustion Rate in Smothering Tank during the Test (Lower Cell)

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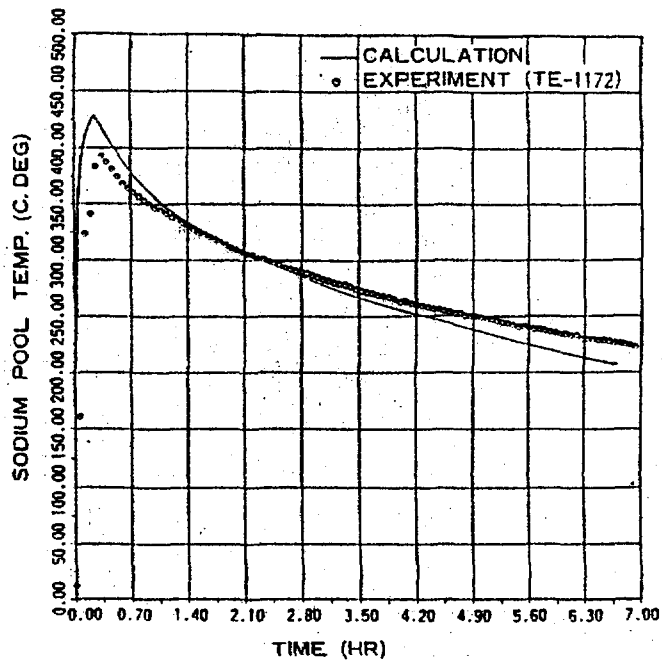

SODIUM POOL TEMPERATURE

Fig. 9 Sodium Temperature Drop in Smothering Tank
- Comparison between code and test results -

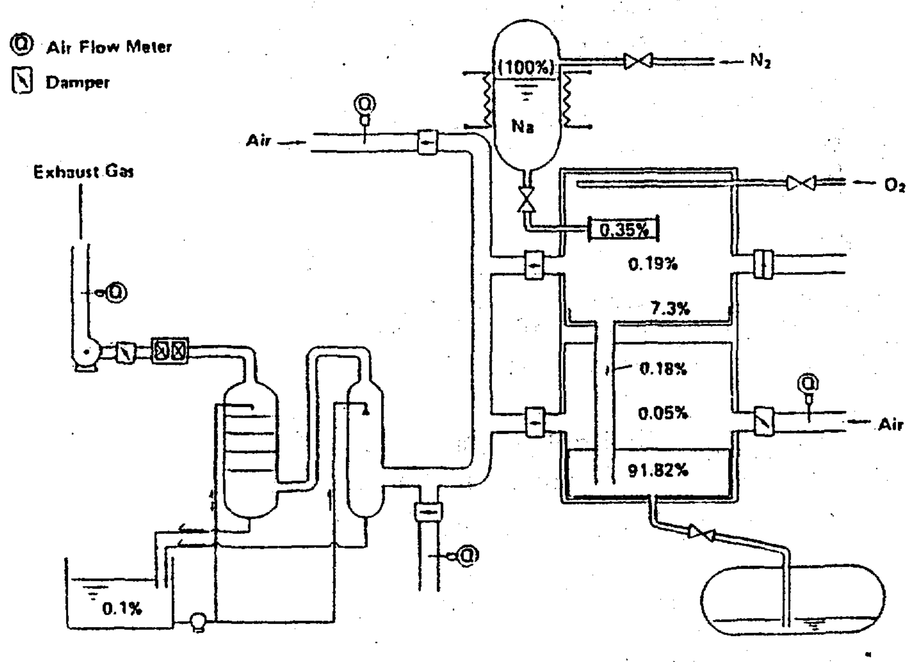

Fig. 10 Post-Test Sodium Distribution in Test Rig

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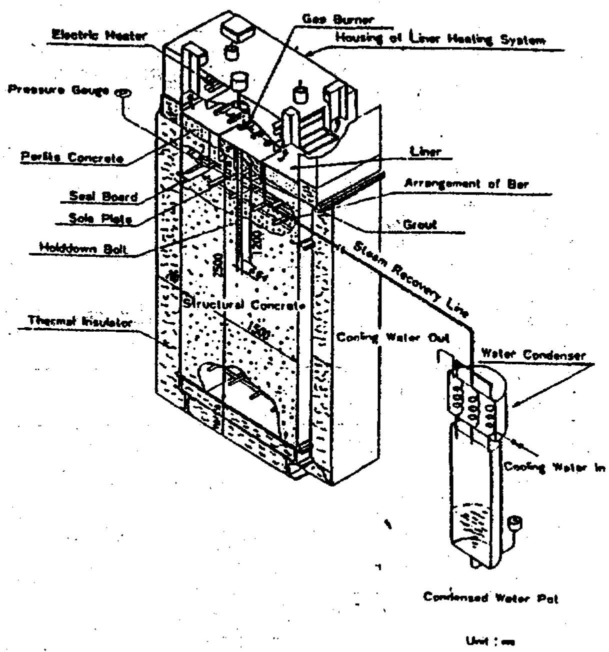

Fig. 11 Test Section for Thermal Conduction of Steel Lined Concrete

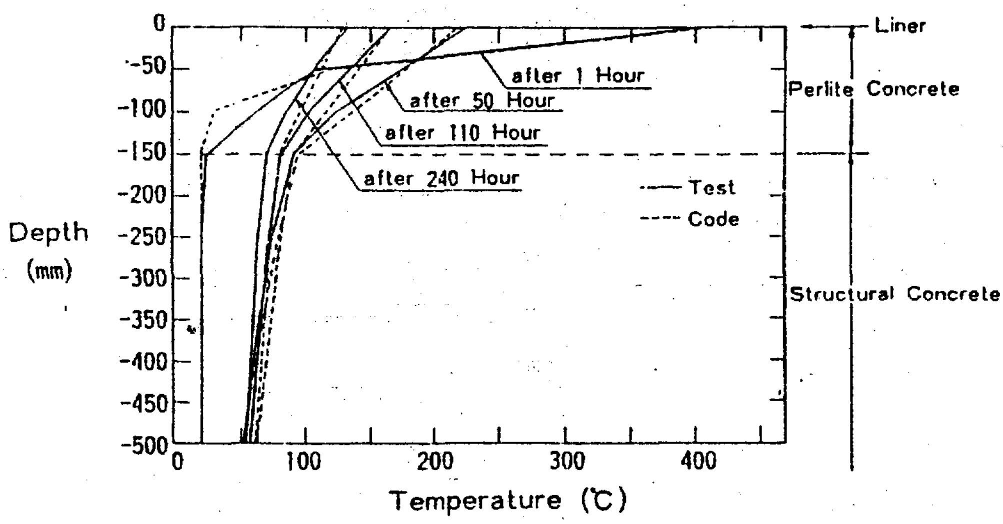

Fig. 12 Change of Vertical Temperature Profile in Perlite and Structural Concrete of Test Section

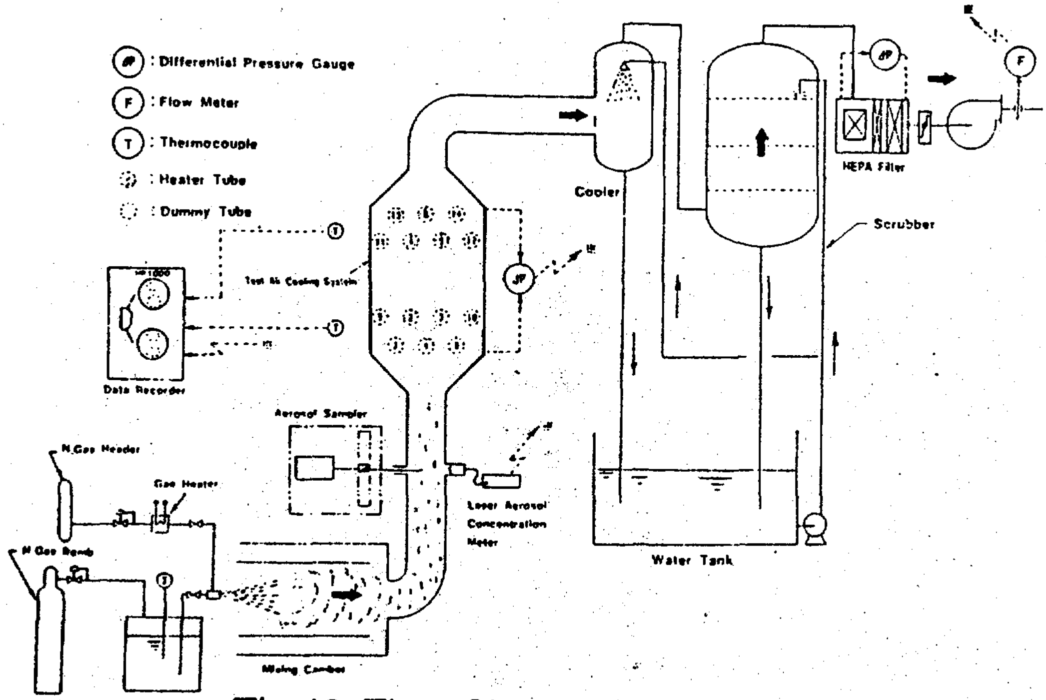

Fig. 13 Flow Sheet Diagram of ACS Heat Transfer Test Rig

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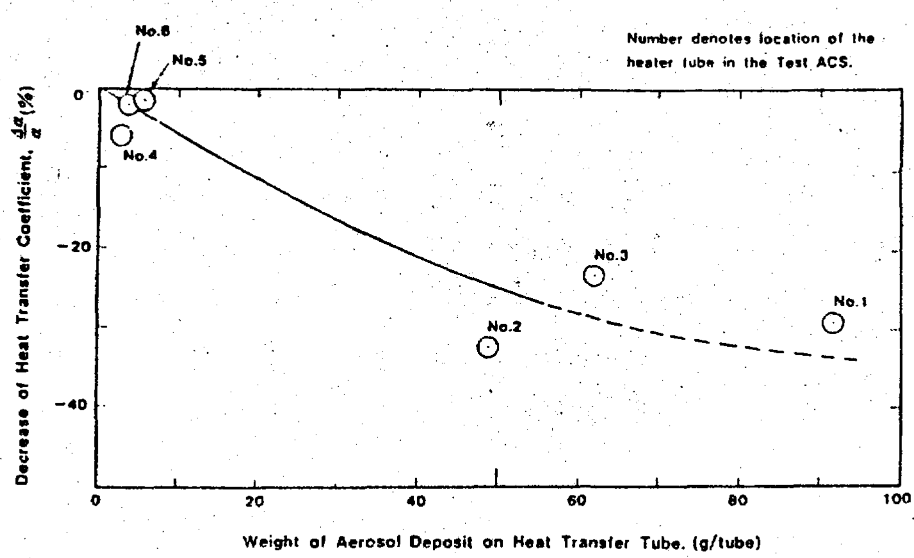

Fig. 14 Decrease of Heat Transfer Coefficient due to Aerosol Deposition

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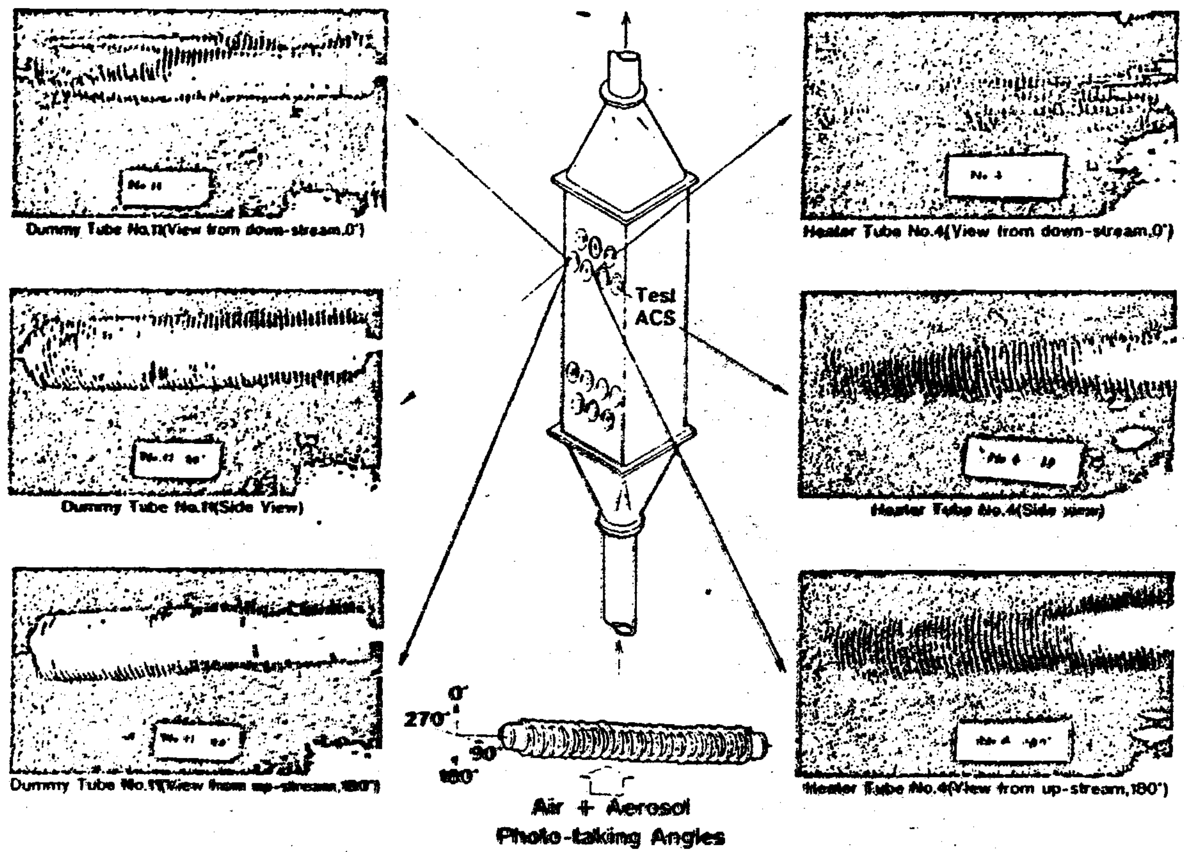

Photo. 1 Aerosol Deposit on Dummy and Heater Tubes in the Third Stage of the Array