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SODIUM FIRES - PROGRESS ACHIEVED IN RESEARCH AND EXPERIMENTAL RESULTS

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ABSTRACT

This paper describes the sodium fire programs undertaken by the CEA's Nuclear Safety Department. Experimental results concerning sodium ignition and combustion, sodium fire suppression, sodium aerosol filtration and sodium-concrete contact reactions are given and the applications of these results in the Super-Phénix reactor is discussed.

INTRODUCTION

In a fast breeder reactor such as Super-Phénix the greatest sodium fire hazards exist in the secondary loops and, to a lesser extent, in the auxiliary systems (storage drum, cooling system). In fact, for the primary sodium contained in the main vessel only a hypothetical core melt-down accident would be likely to cause leakage past this barrier. Even so, only small amounts of primary sodium would be liable to escape from the vessel; however they would be discharged under pressure through small cross section cracks, generating a spray fire which would develop under the reactor dome. In this event the dangers would be the temperature effect, the associated pressure effect and radiological hazard due to the contaminated aerosols.

The amounts of secondary sodium likely to escape from the systems may vary from a few kilograms to several tons, according to the nature of the leak. The pressure, which is not very high in the circuits, drops rapidly in the event of a large leak with the result that the metal runs out and burns in a pool. This type of fire must therefore be studied both from the standpoint of combustion dynamics and associated phenomena, and from that of prevention and suppression.

This paper describes the research undertaken by the Cadarache Nuclear Safety Department on:

- sodium ignition
- combustion
 - . pool fires
 - . spray fires
- suppression
- sodium aerosol filtration
- sodium-concrete contact reactions.

SODIUM IGNITION

Experimental research was conducted in a 316-liter vessel with a still pool of 100 g of sodium covering an area of 113 cm².

Ignition Limits and Rates

The sodium ignition temperature in dry air is 205 °C [1] (Table I). The variation of this temperature as a function of the oxygen molar fraction is not linear (Figure 1). The minimum oxygen molar fraction at which ignition occurs is 3 %.

TABLE I

Oxygen fraction	0.050	0.075	0.100	0.150	0.21
Ignition temperature (°C)	344 °C	252 °C	228 °C	220 °C	205 °C

Above these limits, the time required for the sodium to ignite is given by the following relation:

$$\log(\theta) = \frac{1}{T} \times e^{(A X_{O_2} + B)} - C X_{O_2} + D$$

where: θ = ignition time (sec)
 T = ignition temperature (K)
 X_{O_2} = oxygen molar fraction.

This experimental law characterizes the ignition time in a particular configuration, and is certainly not applicable to all systems. Nevertheless the phenomenon may possess a specific character corresponding to an exponential form for which the coefficients are related to experimental conditions.

Ignition Mechanism

Tests showed that ignition was always preceded by the formation of nodules on the surface of the metal. This nodule formation alone was not sufficient for ignition to occur. Observation of the surface of the metal with an IR camera showed that the nodule pattern is directly related to supertemperature phenomena which appear on the surface of the metal. The following hypothesis was formulated: the structure of the oxide film is heterogeneous (porosity, structural defects etc.). This leads to uneven oxidation spots at which temperature gradients are established. A mechanism of tangential forces is created by a surface tension gradient (thermocapillary convections) which break through the oxide film resulting in the formation of nodules. The nodules, which are drops of sodium, oxidize and heat up more quickly than the surrounding metal surface because of the high area/volume ratio. The resulting thermal disequilibrium causes ignition.

It is important to note here, that finely divided sodium may ignite even at normal temperature. In this case the reaction area/volume ratio

is so high that the temperature may increase rapidly and cause ignition.

COMBUSTION

Sodium Pool Fires

1. Effects of the Sodium Temperature, the Combustion Surface Area and the Sodium Pool Thickness on the Combustion Rate

Table I shows the results obtained during fires at different initial sodium temperatures and under conditions with varying oxygen concentration. The following conclusions may be drawn from the table:

- the initial sodium temperature does not appear to have a significant influence on the mean combustion rate. This is certainly due to the fact that the temperature of the pool stabilizes during the fire at a value between 570 °C and 750 °C. Under no circumstances was the boiling temperature reached, even when the initial temperature was in the region of 840 °C.
- the mean combustion rate seems to decrease as the combustion area increases. This is certainly due to the convection movements which, for large area fires, hinder oxygen diffusion to the center of the sodium pool. This phenomenon is even clearer when the initial combustion rates are compared: the initial rate of 49 kg h⁻¹ m⁻² for an area of 0.125 m², becomes 36 kg h⁻¹ m⁻² for an area of 1 m² and 27.6 kg h⁻¹ m⁻² for an area of 10 m².

TABLE II

Experiment	Initial Sodium Temperature °C	Vessel m ³	Thickness cm	Area m ²	Mean Combustion Rate kg h ⁻¹ m ⁻²	Oxide Release Rate
Cassandre 3	550	400	5.1	1	24.5	0.31
Cassandre 4	550	400	10	1	26.9	0.365
Cassandre 5	550	400	14	1	26.2	0.385
Cassandre 6	550	400	28.6	1	23.8	0.40
Cassandre 7	550	400	18.3	2	19.6	0.46
Cassandre 8	550	400	9.2	4	17.7	0.43
Lucifer 1	250	400	17.5	2	17.1	0.45
Lucifer 4	140	400	18.5	2	18.5	0.372
Lucifer 5	840	400	20.4	2	17.9	0.427
Drac	200	400	12.8	10	17.7	0.163
ZBCOS	550	22	9.9	0.125	38.4	0.24

The thickness of the sodium pool has no effect on the combustion rate. However the burned sodium mass may be estimated using the formula:

$$M_B = K \cdot S \cdot d$$

where $K = \text{kg} \cdot \text{m}^{-3}$

$S = \text{area (m}^2\text{)}$

$d = \text{sodium pool thickness (m)}$

When d exceeds 26.5 cm the burned mass depends almost solely on the combustion area.

- As regards the amount of burned sodium which is found in the aerosols, it does not exceed 45 % of the burned mass. The aerosols are made up of sodium peroxide. The rest of the burned sodium contained in the combustion pan is in monoxide form with a small proportion of peroxide. After the fire, the proportion of burned sodium in peroxide form is 52 % on average.

2. Humidity Effects

Test conducted in a 22 m³ vessel on the effects of humidity on the combustion rate show that humidity inhibits combustion up to 30 % relative humidity at 20 °C. This inhibiting effect gradually disappears above 60 %, but the mean combustion rate does not reach that obtained in dry atmosphere (Figure 2). This inhibition of combustion is due to the formation of a soda film on the surface of the metal, not as a result of a reaction between the sodium and the water vapor (hydrogen production is imperceptible), but rather by the action of the latter on the oxides formed during combustion.

3. Computer Code

A "Sodium Pool Fires" computer code has been qualified on the basis of the results obtained and is currently being used by Novatome for Super-Phénix calculations.

Sodium Spray Fires

Current research is being conducted from two standpoints:

- experimental research in a 3.7 m³ vessel
- theoretical research, based on experimental results, the purpose of which is to qualify a "Sodium Spray Fires" computer code, written jointly by CEA and NOVATOME. Only the experimental research will be described in this paper.

1. Experimental Research

The purpose of this study is to determine the dimensions of the sodium

droplets produced during spraying and to study droplet combustion and the resulting thermodynamic effects.

a) Droplet Size Determination

The droplet size was determined by sampling droplets in a liquid inert with regard to sodium. This sample was then analyzed with an electron microscope. The results showed a polydispersed spectrum but with a standard log distribution.

It is thus possible to calculate the Sauter radius (\bar{R}) from the following equation:

$$\bar{R} = R_{50} \exp. (-1.5 \log^2 \sigma_R)$$

Studies are currently being carried out to relate R_{50} and σ_R to the spray parameters: differential ejection pressure, orifice diameters, pressure drop in jet, physical properties of the ejected liquid.

b) Combustion Study

This study is designed to provide significant combustion data, i.e. sodium droplet combustion rate, energy distribution and transfer in the system in which the fire is developing. The parameters are droplet size, the oxygen/sodium molar ratio and the sodium temperature, and the related measurements are those of temperature and pressure, nature and proportion of the combustion products.

SUPPRESSION

There are two types of sodium fire extinguishing systems: passive and active. Both are based on the principle of isolating the oxidant from the fuel.

Passive Systems

Apparatus has been developed from tests conducted with smothering pans in a 400 m³ caisson with which the following results were obtained:

- for one metric ton of sodium discharged only 30 kg burn,
- the combustion rate is reduced by a factor of 10,
- the temperature of the sodium in the pan falls immediately.

Further tests were conducted to study pan interconnections in order to increase the system retention capacity and to cover the entire potential leakage area. The results obtained by interconnecting four pans marked a further step forward: out of the ton of sodium poured into the pans only 10 kg burned.

Active Systems

The Marcalina powder research program [2] covered the storage and use of this powder in portable, mobile and built-in devices. Devices of different capacities (9, 20, 40, 70, 150, 320, 1000 liters and more) have been designed. The physical and chemical behavior of the powder in these reservoirs is known. These devices are now in use in CEA facilities where sodium is handled. Research was conducted in the 400 m³ caisson using a built-in installation comprising reservoirs (1/3 Super Phénix size) and piping (length equivalent to that of the Super Phénix systems). This installation operates at the material flow rates and concentrations (material/ carrier gas) adopted for Super Phénix.

FILTRATION AND PREFILTRATION OF SODIUM AEROSOLS

Prefiltration of sodium aerosols is necessary in view of the minute amounts of aerosols trapped by a very high efficiency filter-cell as shown in Table III.

TABLE III

FILTER	Surface Area m ²	Test Flow Rate (m ³ /h)	Sodium Retention Capacity (g)
SOFILTRA	45	1 500	270
ASTROCEL I (AAF)	21.4	1 500	126
ASTROCEL II (AAF)	34.5	1 500	177

Prefilter tests conducted with a 1 500 m³ ventilation loop installed next to the 400 m³ caisson [3] showed that no commercially available unit meets the required specifications. CEA therefore undertook to improve two water scrubber prefilters. One was the Colag prefilter on which successive improvements have increased the efficiency rating from 84 %, obtained with the initial device shown in Sketch 1 (Figure 3), to 99.2 %. The other was the aqualine R filter (original filter - sketch 2, Figure 3) for which the efficiency rating increased from 70 % to 99,9 %.

SODIUM - CONCRETE REACTION

Previous test showed that it was necessary to cover the concrete with steel plating in order to prevent a sodium spray fire caused by detonation of the hydrogen produced by reaction between the sodium and the water contained in the concrete [2].

The purpose of the present study is to analyze the sodium concrete reaction. The initial tests seem to indicate that the hydrogen production rate depends on the thickness of the concrete layer. For thin concrete

slabs an appreciable fraction of the water may be evacuated from the cold face. This fraction diminishes as the concrete thickness increases. The concrete may reach temperatures on the order of 800 °C, and subsequent analysis has shown that concrete erosion by the sodium results essentially from the alkaline melting of certain aggregate components.

CONCLUSION: SUPER-PHENIX APPLICATIONS

The overall findings of all CEA research programs are used for safety considerations in SUPER-PHENIX.

The sodium pool fire computer code is used to predict the thermodynamic consequences of a possible sodium fire in all rooms where a sodium hazard exists. This code is used to determine the containment design according to the mechanical possibilities of the room in question. It is also used to calculate the amount of aerosols which would be extracted from a room under ventilation conditions, in order to determine the prefilter efficiency required to protect the very high efficiency filters. Whenever a sodium fire hazard exists, measures are taken to suppress the effects of such fires: metal plating and thermal insulation of concrete, installation of smothering pan catchment devices, provision of hand fire extinguishers for minor leaks and — for major outleakage — built-in powder spreading systems for inaccessible room and mobile powder spreaders for accessible locations. These powder spreaders are supplied from permanent installations comprising powder storage tanks and supply lines leading to sodium fire hazard rooms.

REFERENCES

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2. Y. FRUCHARD, "Sodium Fire Studies in France. Safety Tests and Application on an LMFBR", Chicago conference — October 6 - 8, 1976.
3. G. DUVERGER DE CUY, "Sodium Oxide Aerosol Filtrations", IAEA specialist's meeting on sodium fires and prevention, Cadarache, November 20 - 24, 1978.

Fig.1

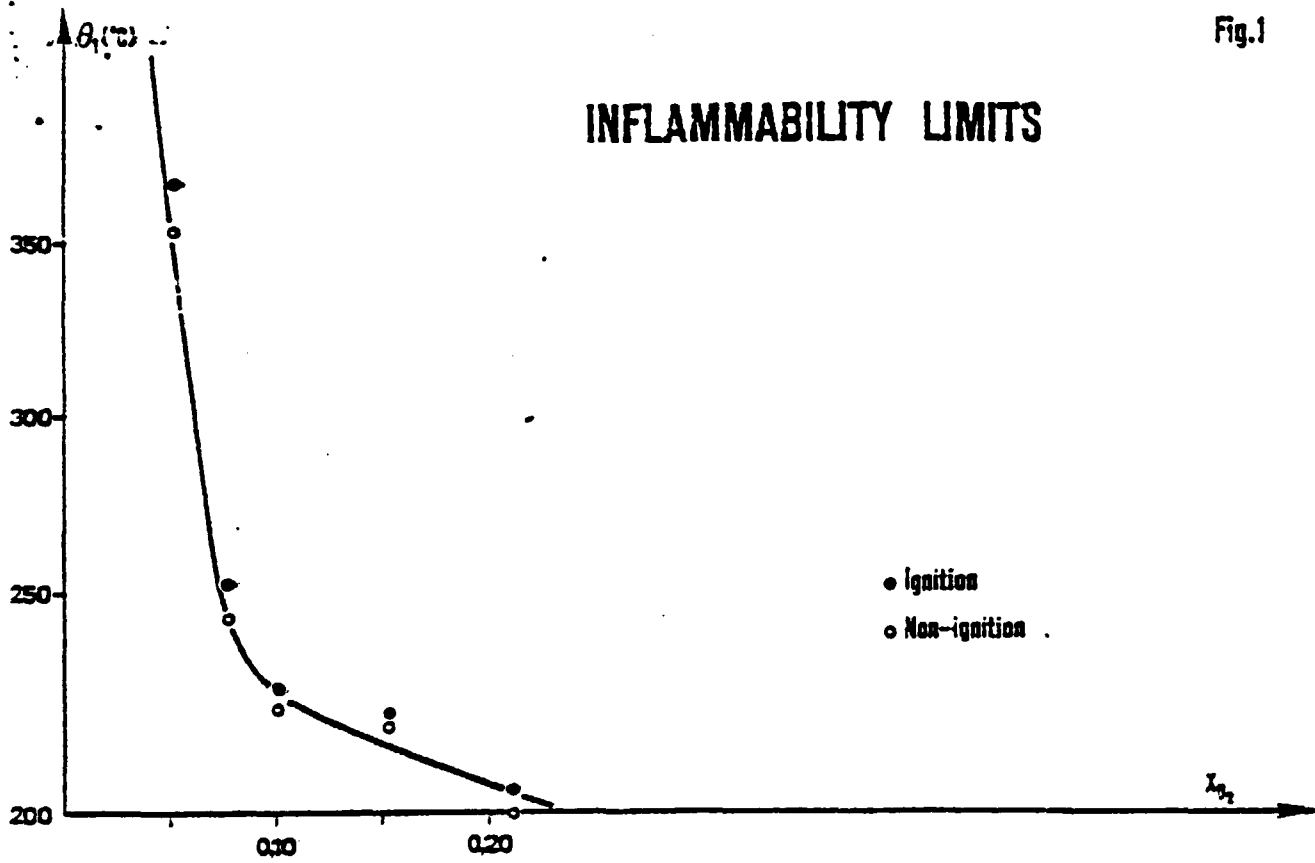
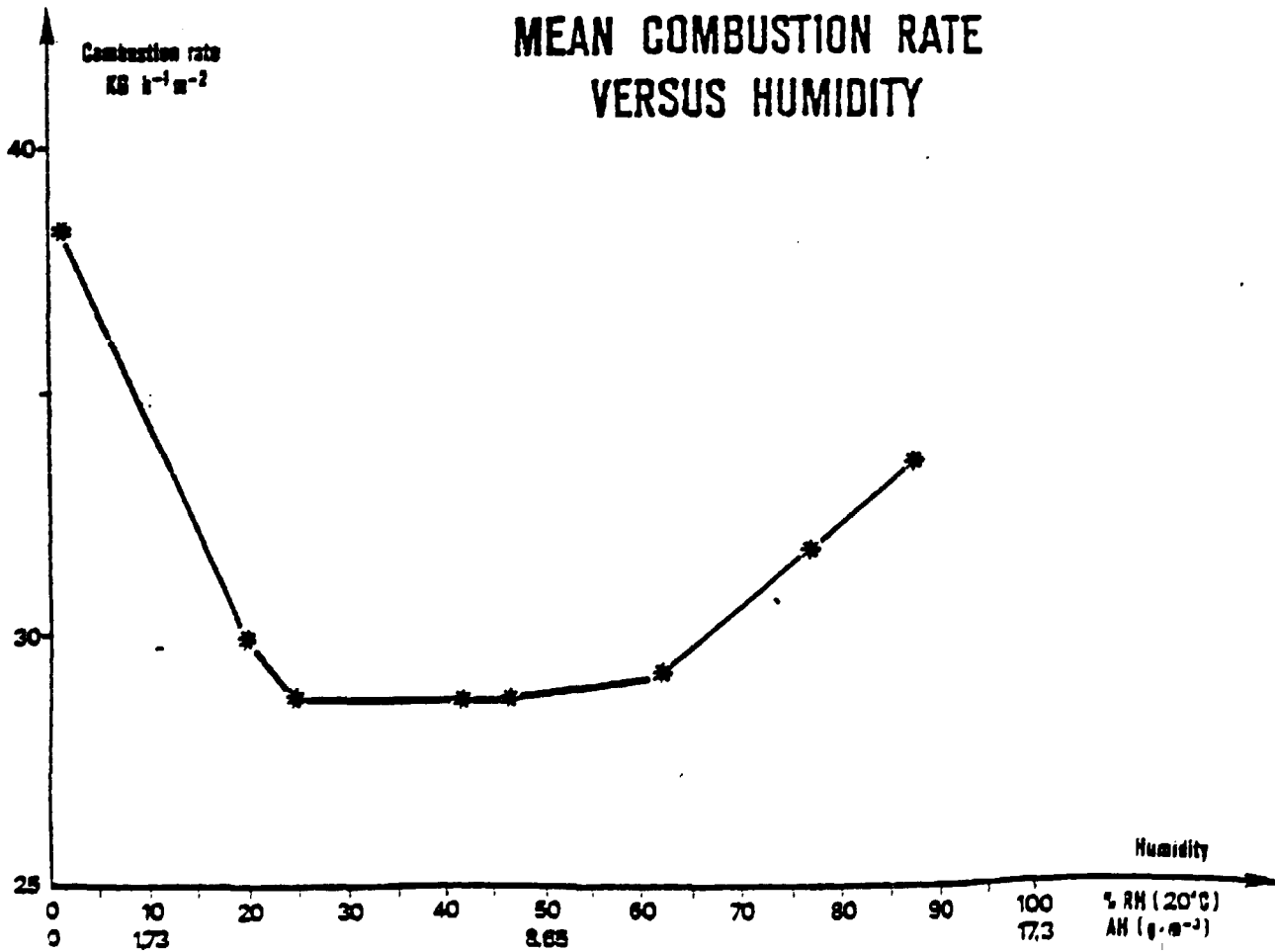
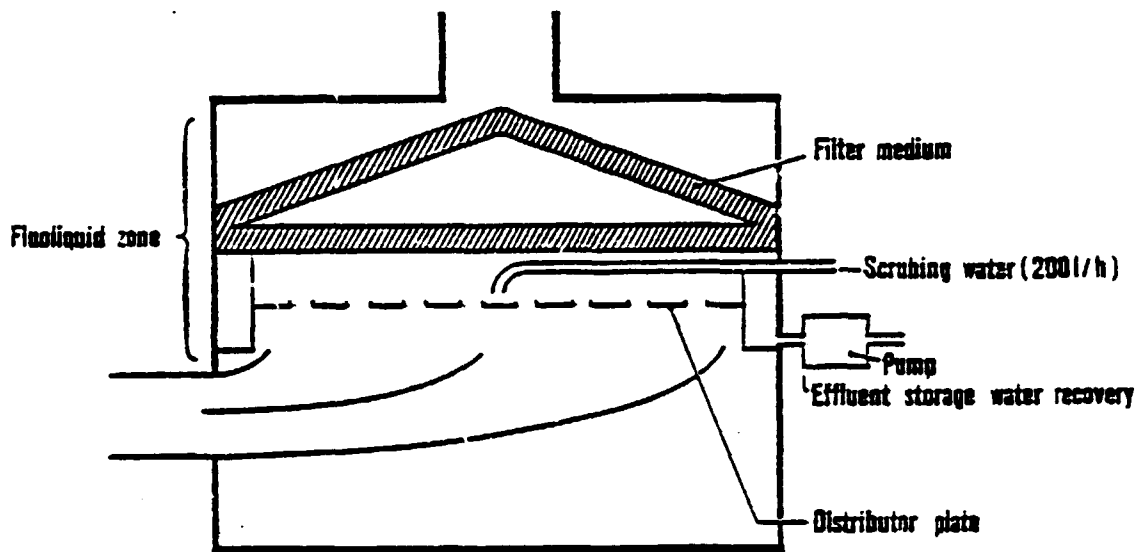


Fig.2



Schema 1
COLAG (A.A.F.)



Schema 2
**AQUALINE R (N.E.U.)
 OPERATING DIAGRAM**

