Fire-Fighting Procedure and Estimation of Fire Consequences in Nuclear Plants

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ABSTRACT

Research and development studies concerning the combustion and the behaviour of the various materials encountered in nuclear reactors and facilities are carried out by the CEA in "fire laboratories" at CADARACHE. The objective is to place qualified numerical and technical tools at the disposal of designers, project managers and safety analysts. Qualification is supported by experiments and physico-chemical models. Results are given on pyrophoric metals (mainly magnesium) and carbon compounds (inflammable liquid and solid) combustion and on fire extinguishing procedure.

KEYWORDS : fire, safety, magnesium, dodecane, combustion, extinction.

1 INTRODUCTION

In nuclear safety, the role played by the containment and its associated ventilation system is of prime importance. An accidental fire taking place in a room may produce a failure of the containment and a release of radioactive products outside the building. The following guide lines are applied :

- the containment and its ventilation network are designed to withstand the mechanical and thermal consequences of the postulated fire,
- the products are trapped within the containment by properly protecting and dimensioning the filter systems,
- the consequences of the fire are mitigated by passive or active means of extinction,
- if necessary, the instructions to be followed during the incident, particularly concerning the management of the ventilation network, are derived from models and computer code pre-calculations,
- adapted rules are settled in order to make the plant operational again after the incident.

The resulting procedures can be adapted to any compound and to any facility : that should be the case of industrial facilities carrying potential release of toxic and/or corrosive gaseous or solid products into the atmosphere (chlorine, chlorinated by-products, cyanide, bacteria's...).

Fire-fighting studies have been carried out by the CEA (Commissariat à l'énergie atomique) at the nuclear research centre of CADARACHE, for many years now, and they have involved fuels of very different nature such as pyrophoric metals and carbon compounds.

2 EXPERIMENTAL FACILITIES AND INSTRUMENTATION

The fire laboratories include :

- four stainless steel cells (316l, 3.7m^3, 4.5m^3 and 22m^3 cylindrical volumes) withstanding high pressure ; they are useful for parametric studies on small fuel quantities (several kg to 100 kg),
- two concrete rectangular vessels (400m^3, 3600m^3) and one tower (2000m^3), all of them designed for full or large scale experiments (up to 30 tons in the case of sodium) ; the vessels are equipped with ventilation circuits including aerosol pre-filters and filters, the tower is protected by self opening windows at its top.

Instrumentation provides continuous mass and heat balances :

- mass loss of the fuel by weighing,
- temperature (fuel, flame, gases, walls, structures),
- pressure (gases, pressure drop in the venting ducts),
- concentration of the various species in fuel, gases, inlet and outlet ducts (especially oxygen, carbon oxides, hydrogen, and low carbon content species),
- aerosol granulometry, concentration, deposition rate,
- flow-rate (inlet and outlet ducts, ventilation circuits),
- heat flux (walls of the vessel and of the exhausting duct).

3 EXPERIMENTAL RESULTS

3.1 Pyrophoric metals : magnesium pool fires.

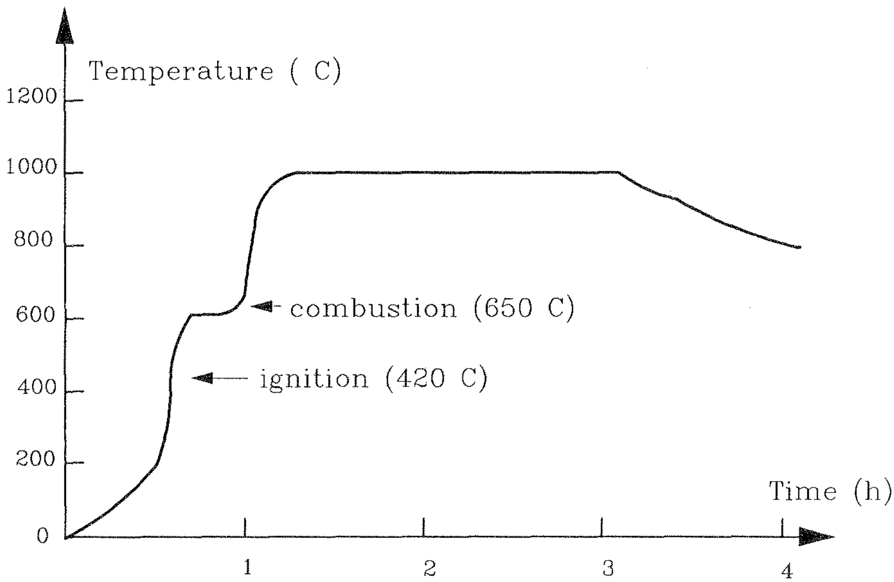
Magnesium cuttings [1] from decladding operation of nuclear fuels are stored in large silos : those cuttings are characterized by their affinity with oxygen and their inflammability.

3.1.1 Combustion and aerosol filtration

Ignition was initiated by electrically heating cylindrical pans filled with 10 kg of magnesium cuttings. The pan cross section provided a 0.125 m^2 pool area. The fire always follows the same course (fig. 1). The first smoke appears at around 420°C and overall combustion up to around 650°C, the melting point of magnesium. The temperature becomes stable around this value until overall melting of the metal is reached, then rises again up to 1050-1060°C close to the boiling point (1107°C). Combustion residues are composed of magnesium oxide (MgO) and magnesium nitride ($Mg_3 N_2$) (X-ray analysis). The aerosols released are made up of magnesium oxide (MgO). Average combustion rate is 30 kg.h^{-1}m^{-2}.

Very high efficiency fibre-glass filters (designed for a 280 $m^3.h^{-1}$ flow rate through a filtering surface of 3.5 m^2) were quickly plugged. The pressure drop of the filter rose from 200 pascals to 900 pascals and the average quantity of (MgO) aerosols deposited was about 35 $g.m^{-2}$ of the filtering surface.

Figure 1. Magnesium cuttings layer



3.1.2 Pool fire propagation inside a storage silo mock-up

The objective was to study fire propagation into a cuttings storage from a hot point represented by a small pot filled with magnesium powder and heated by an electrical 500 W powered element.

The mock-up (fig.2) was made up of a cylindrical, 510 mm high, 500 mm in diameter, steel containment equipped with an air blowing fan and an extraction system that provided a constant air renewal rate.

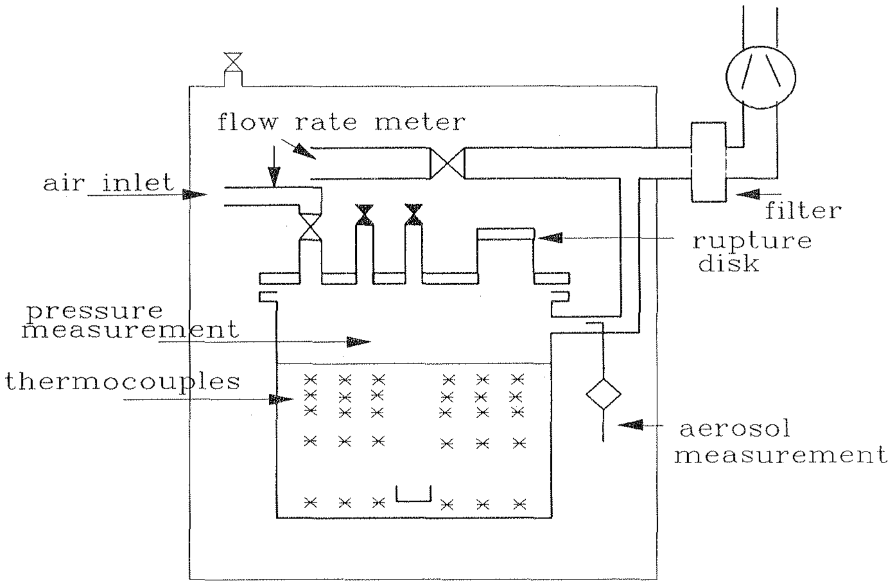
The quantity of magnesium contained in the mock-up was 50 kg.

When the hot point was in the upper part of the cuttings layer, increasing the extracted flow rate from 300 $l.h^{-1}$ to 1000 $l.h^{-1}$ resulted in larger reaction volume : 20 l instead of 2.5 l and local temperatures to over 700°C.

When the hot point and a 1000 $l.\ h^{-1}$ flow rate of air were supplied in the lower part of the mock-up, a sudden propagation was observed from the reaction zone to the whole of the magnesium some 5 hours later on, the temperature of the magnesium exceeded 600°C in the vicinity of the ignition point.

Combustion residues were enriched in MgO (about 100%) in the first layer of powder and crust which turned from white to black, in the middle, yellow to green residues were made of MgO (58.5%) and Mg3N2 (41.4%) and a large part of unburnt Mg remained in the bottom (48.9% Mg, 32.2% MgO, 18.9% Mg3N2).

Figure 2. Fire propagation inside a cuttings storage



3.1.3 Magnesium pool fire extinction

The extinction tests were carried out :

- on a small scale (10 kg) in order to select the most suitable of the potential extinguishing powders ; 5 kg of Talcum, sand, cement, HP SICLI powder, MG 15 powder, CK 23 graphex-totalite, marcalina, TEC powder, cryolite were tested over $0.125m^2$ cuttings pans,
- on a larger scale in order to validate the material selected.

The TEC and MG 15 powders were inefficient as the organic products contained in these powders ignited when in contact with the fire. To achieve a complete extinction, two 5 kg sprays of talcum were required. Moreover, with cement and sand, the fire re-started quite violently after the first spreading with crackling and orange flames and, in the case of TOTALITE, the analyses of gas sampled from below the fire revealed the presence of cyanide.

On the other hand there seemed to be no restrictions for the use of SICLI HP, marcalina, graphex and cryolite. The last one was chosen for its action on magnesium pool fires in view of its low cost.

Validation tests were run on increasing cuttings layers (table I). In these tests, the necessary amounts of cryolite depended more on the layer area than on its depth.

TABLE I. CRYOLITE EXTINGUISHING EFFICIENCY

Combustion surface m^2	Thickness of the magnesium layer cm	Magnesium mass kg	Cryolite used for extinguishing $kg.m^{-2}$
1	10	55	19
1	20	116	17
1	40	212	21
2	10	125	30
4	10	224	35

3.2 Pyrophoric metal : sodium pool fires

Related to the fast neutron reactor safety, sodium fires have been widely studied since 1970[2]. On the end of 1989, an experimental program, named ESMERALDA[3], was achieved in the 3600 m^3 concrete caisson and in the 2000 m^3 tower involving several tons of hot liquid sodium up to 20 tons over pool areas as large as 50 m^2.

Special attention was paid to extinguishing means[4]such as passive devices (funnelling floors, smothering pans) or active automatic operations (on-site spreading of a specific powder MARCALINA based on sodium and lithium carbonates). As in the case of magnesium pool fires, the use of sand and cement should be prohibited. The techniques designed in the actual reactors were proved as efficient as predicted from the previous smaller scaled tests ; rules were derived for waste management and plant repairing procedures.

3.3 Organic materials

Large quantities of TBP-dodecane mixtures, category 2 inflammable liquids, are currently used in nuclear fuel reprocessing plants. Heavy mineral oil is often used as a pump coolant and several oil fires have been already detected. Long term storage of radioactive bituminous wastes could be jeopardized by the radiant energy supply from the radioactive species themselves. PMMA (polymethylmethacrylate) is a component of the "glove-boxes" used in the handling of radioactive material.

The characteristics of TBP-dodecane combustion have been already studied[5] : therefore, the experimental program concerning them involved mainly large-scaled tests. For the other materials, the experimental program started on rather small quantities (table II).

3.3.1 TBP-dodecane mixture

For so large pool areas (table II), the mean values of the combustion rate, averaged on the main fire duration, depended on the thickness of the pool and not on its area. All the tests showed the same course. As an example, experiment 2 results are presented in figure 3. The ignition of the pool is characterized by a transient gas pressure rise the amplitude of which depends on the ability of the venting network to absorb the energy released by the fire. Then, gas pressure and exhausting gas flow rate decrease gradually until the flame dies out due to lack of oxygen in the vessel (usually, the oxygen concentration of the gases at that time was around 15%).

Table II : ORGANIC MATERIAL - EXPERIMENTAL CONDITIONS AND RESULTS

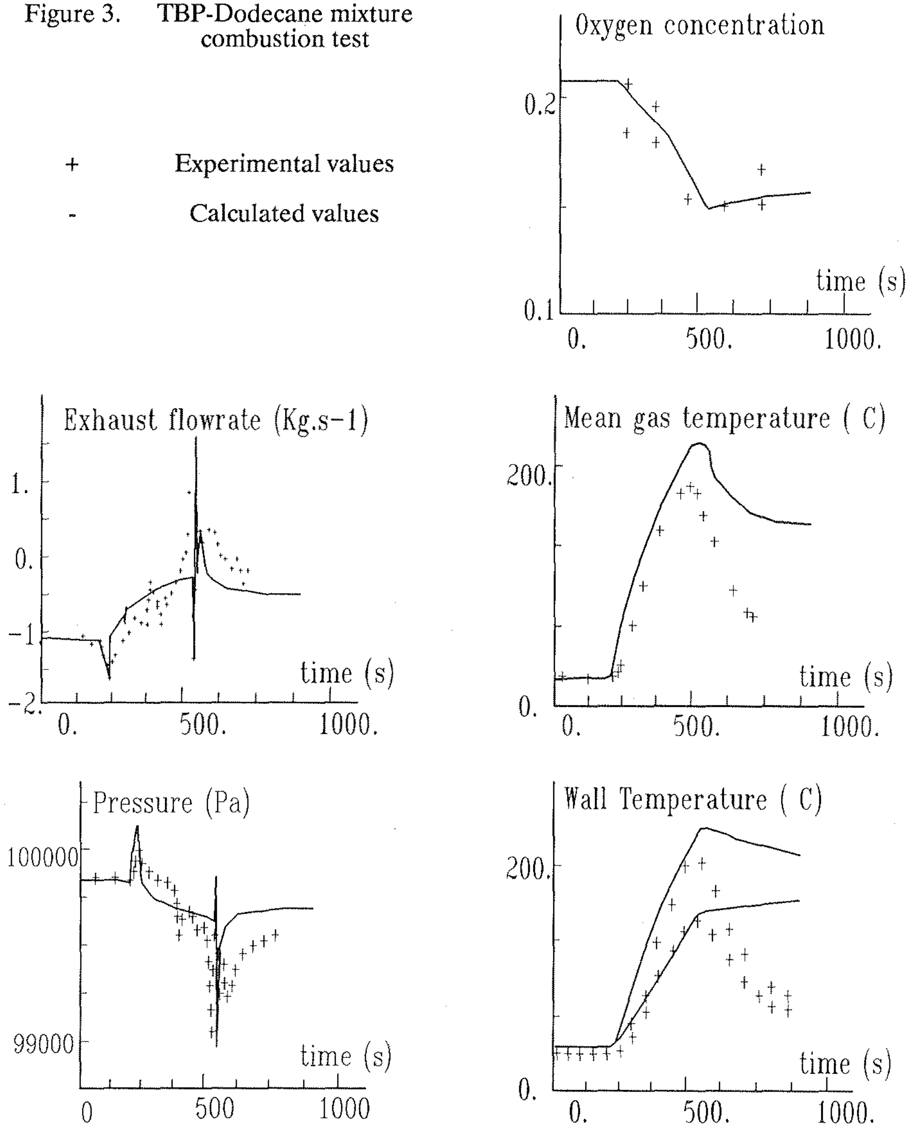
Fuel	Test	Pool or sheet characteristics	Vessel volume (m^3)	Venting flow rate ($m^3\ h^{-1}$)	Mean combustion rate ($g.m^{-2}.s^{-1}$)	Fire duration (min)	Mean gas temperature (°C)	Maximum overpressure (hPa)
Dodecane-TBP	1	50 l, 1 m^2	400	Function of overpressure	25.3	6.25	150	-2
	2	50 l, 1 m^2	400	Function of overpressure	27.5	5.75	175	-1.5
	4	200 l, 1 m^2	400	Function of overpressure	12.0	16	115	0
	5	1000 l, 20 m^2	3600	Function of overpressure	25.6	3	350	365
OIL	1	78.5 cm^2, e = 5 cm	4.5	-	5.4	39	33	10
	3	628 cm^2, e = 20 cm	4.5	-	10.4	3.4	110	238
	6	314 cm^2, e = 20 cm	4.5	-	5.5	10	75	148
BITUMEN	11	78.5 cm^2, e = 2 cm	4.4	-	3.8	66	95	200
	12	78.5 cm^2, e = 5 cm	4.4	-	2.7	94	110	(55)
	13	196 cm^2, e = 5 cm	4.4	-	4.2	36	115	180
	14	78.5 cm^2, e = 5 cm	4.4	45	3.2	186	95	-
BITUMINOUS WASTES	W/12	78.5 cm^2, e = 5 cm	4.4	-	17.5	24	70	180
	W/13	196 cm^2, e = 5 cm	4.4	-	10.1	16	80	240
	W/14	78.5 cm^2, e = 5 cm	4.4	55	15.5	30.5	75	-
PMMA	6	Horizontal, e = 8 mm 0.8 x 1.25 m^2	22	220	3.2 $g.s^{-1}$	36	200	1
	8	Vertical, e = 8 mm 0.8 x 1.25 m^2	22	220	1.6 $g.s^{-1}$	87	150	0

At the end of the fire, gas temperature and pressure decrease sharply, involving a reverse flow (air inlet by the exhausting pipe) and a short re-ignition. Wall temperatures decrease as soon as the fire stops.

Figure 3. TBP-Dodecane mixture combustion test

\+ Experimental values

\- Calculated values



3.3.2 Motor oil

The first series of tests was performed in a tightly closed steel vessel in order to get more accurate mass and heat balances.

For 0.125 m^2 pool area, the combustion rate depends on the thickness but also on the depth of the pool. The course of the combustion is limited by the amount of oxygen available.

3.3.3 Bituminen and bituminous wastes

During bitumen and bituminous waste experiments, a radiant energy was supplied and maintained all along the fire ; in the event of it being turned off, the flame would disappear. A volume growth with overflowing was observed during the combustion of bituminous wastes. Vaporisation rate was higher for bituminous wastes than for bituminen because exothermic reactions of mineral species (nitrates compounds) occurred during the combustion. Venting the fire room increased the fire duration and the total burned fraction but the mean combustion rate did not vary notably.

3.3.4 PMMA

PMMA materials were presented as vertical or horizontal sheets, 1m^2 area. The flame extended under the horizontal sheet, then, the combustion rapidly reached an overall conflagration.In case of the vertical sheet, the flame sprayed upward and the sheet was cut in the middle. This explained a longer fire duration, smaller vaporisation rate and in-cell mean gas temperature.

4 Theoretical approach

For metal fires, the main phenomena were described and computed in a code system named PYROS II[6]. That included thermodynamic and chemical analysis of ignition, combustion, extinguishing, water and concrete reactions, aerosols in cell behaviour and atmospheric diffusion into the environment. In case of liquid sodium, the results were already applied to safety analysis of the fast neutron reactors.

For carbon compound fires, a 1D model named FLAMME[7]was designed to take into account the differences between metal and organic material combustion. A first version, FLAMME I, is limited for single combustible material, fire room and fire place ; a second version, FLAMME II is extended to several fires either simultaneous or in a staggered sequence.

4.1 FLAMME computer code

Derived from the HARVARD code, the FLAMME I model divides the fire room into homogeneous zones - fuel, flame, upper cell hot and lower cell cold atmosphere, structures, walls - among which mass and energy are exchanged.

Three options are available in order to take into account ventilation systems:

. a simplified model using Bernoulli's law,

. a stack release model, named CHEMINEE, to calculate pressure and temperature transients and heat loss through the cladding and along the exhaust circuit,

. a model describing a ventilation network (LIQUINET) (flow-rate and temperature transients, and aerosol transport).

Based on the same model, FLAMME II evaluates more accurately the mean shape factors in the radiative energy exchanges among the various zones.

A library includes the physical and chemical properties of the materials (various fuels, concrete, steel, ...).

4.2 NUMERICAL RESULTS AND CODE VALIDATION

Experimental results were compared with numerical runs from FLAMME I specially concerning TBP-dodecane mixtures and motor oil. As an example, test 2 of the TBP-dodecane mixtures series was calculated with the LIQUINET venting option (fig 3). Numerical results were in a good agreement with the experiment. The main characteristics of the fire are satisfactorily predicted : fire duration, oxygen concentration, in-cell gas temperature and pressure and exhaust flow rate fitted the experimental evolution.

Due to the lack of instrumented tests on multiple sources of fire in the same room, FLAMME II is awaiting validation.

5 CONCLUSION

The various combustible materials studied - magnesium cuttings, hot liquid sodium, carbon compounds - illustrate how far the theoretical and experimental studies have to be performed to provide the necessary data to designer, safety analyst or operator of a nuclear facility. An extensive program was developed for sodium fire control. Today, fire propagation and extinguishing tests on a mock up are satisfactory for magnesium cuttings or bituminous wastes storage. Large scale or full scale tests and subsequent computer codes are necessary for TBP-dodecane mixtures and motor oil.

Experiments concerning organic material fires illustrated the effect of the layer thickness on the combustion rate and of the venting system (location of the air vents, flow-rate...) on the transient gas pressure. Prompt gas cooling when the fire stops, followed by a considerable in-cell pressure drop drags in fresh air that may result in either a fuel re-ignition or an explosion of unburnt gases.

Therefore, the containment must be designed to withstand not only high gas or wall temperatures but also to cope with sharp over- and under-pressure transients.

All these results will improve the data bank of the computer codes and make more realistic their predictions, they will also be integrated in an expert system and render the handling of such potentially hazardous materials safer.

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