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Sodium pool fires consequences on a confined vessel and on the environment

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ABSTRACT

This paper presents the PYROS I Code used in France to calculate the effects of a sodium pool fire on a vessel and his validation range. The results or the atmospheric behaviour of the aerosol are given.

Predicting the consequences of large sodium fires in large cells from the results of small scaled experiments, claim attention on scale effects.

1. SODIUM POOL FIRES CONSEQUENCES ON A VESSEL

Various pool fire tests performed in small and large cells (from 4.4 to 3600 m^3) (table I) involving several kg of sodium to five tons, resulted in a computer code PYROS (I). PYROS foresees the thermodynamical and chemical consequences of a sodium fire and should be used in :

- designing the building,
- determining the containement and the ventilation, pre-filtration and filtration systems,
- protecting the walls against thermal and chemical effects (conducting systems, concrete damage, static engineering safe-guards as funnelling floors, catch or smothering pans),

- designing dynamic safe guards as extinguishing powders,
- estimating harmful effects of the sodic released aerosols in the buildings and on the environment.

From the tests already performed in the large fire test program ESMERALDA, comparison between precalculated and experimental results allows to verify if these objectives are fulfilled.

The main features of the PYROS code involve :

- modelling of the cell,
- combustion equations,
- aerosol behaviour,
- venting systems.

1.1 Modelling of the cell

Mass and heat transfer take place between five main thermodynamical systems : (figure 1)

- the gaseous atmosphere,
- the sodium pool,
- the crust surface,
- the flame,
- the conducting systems.

Each of the first four systems is characterized by a mean temperature. Heat and chemical reactions are supposed to be uniformly distributed in each of them.

The gaseous atmosphere consists of gases (N_2, O_2, H_2O vapour) and aerosols (oxides, hydroxides). Thermal gradient at the surface of the pool is taken into account through the crust system. Thermal energy of the crust surface is exchanged with the flame and the pool.

The conducting systems represent the structures and the walls attached to the cell. Heat transfert between the walls and the gaseous media around them are convective and radiative. The wall and structures in contact with the sodium pool exchange energy with it by monodimensional conduction.

1.2 Combustion equations

The model allows for pool fire. Spray fire could be simultaneously introduced by the way of a breached pipe. Only a part of the leaking sodium is assumed to burn instantaneously. Its heat combustion is fully transferred to the gaseous atmosphere. The other part feeds the pool. Flow rate of leaking sodium and percentage of it burning are input data.

"Wick" process is used as a model for pool fire. It describes the successive steps in sodium pool burning (inflamation, quasi-steady state, self extinguishment).

During the inflamation step, the burning rate for the vapor phase reaction depends on the area and the initial temperature of the pool. At the quasi steady state step, it follows a GARELIS (1) type law and depends mainly on the concentration of oxygen and on gas temperature. During the self-extinguishing step, a corrective term is added.

1.3 Aerosols

Aerosols are generated in the flame as Na_2O. Part of them is transferred to the gaseous atmosphere, the remainder is supposed to fall down into the pool. The transferred fraction is a constant introduced as an input data.

It is assumed that the aerosols included in the gaseous atmosphere are uniformly and instantaneously distributed, changed into Na_2O_2, and at the same temperature as the gaseous atmosphere. In order to allow for aerosol thermal effects, emissivity coefficients are empirically related to their concentration.

Settling rate of the aerosols is assumed to be proportionnal to their concentration. The exponential coefficient is an input data which depends on the size of the cell and whether the walls are vertical or horizontal.

1.4 Ventilation systems

Usually, the containment is an enclosed volume. However one may introduce various ventilating circuits. Inlet or outlet flow rate or pressure drop coefficients are used as input data. The BERNOULLI and SAINT VENANT laws are applied.

The air enters at an initial temperature and goes out at the gaseous atmosphere temperature. Various venting devices could be simulated : holes (in order to simulate lacks of tightness) air lock, under or over-pressure valves.

1.5 PYROS I validation

The PYROS I A version was validated in the range of the available experimental tests :

- initial pool temperature from 110°C to 800°C,
- pool area from 0,6 to 50 m^2,
- sodium mass from 10 to 5000 kgs,
- cell volume from 4.5 to 3600 m^3,
- spill over a short time (less than 5 minutes) and negligible spray,
- closed or ventilated cells (15000 $m^3\ h^{-1}$ flowrate).

The usual accidental fire conditions in large facilities fall out of the validation range and some parameters of the combustion model have to be extrapolated and verified. This concerns mainly the various processes which are not described in the model or which are empirically ruled.

In large cells, Oxygen diffusion may play a role in regulating the burning rate as well as the whole gases movements over the pool. In the PYROS model, Oxygen diffusion has been neglected and convective movements have been taken into account from the results of tests in 4.5 m^3 to 3600 m^3 cells through empirical laws relating the burning rate with the ratios between floor equivalent size and height of the cell, and, between pool equivalent size and floor equivalent size.

Sodium pool temperature plays a role in the early stage of the fire and during the self extinction step. High initial pool (500°C) temperature allows for conservative calculations and makes sure the fire to develop above the whole pool area. Low initial pool temperature (200°C) is calculated in specific operating conditions to preclude fire development :

such assesment claims for verification.

Self extinguishment of the fire comes from either oxygen concentration decrease or oxyde surface layer growth. Near boiling point sodium temperature may prevent the formation of an oxyde layer. Furthermore the model does not allow for sodium ebullition.

Various pool fire tests indicated that the burning rates does not depend on the thickness of the pool (figure 2) when higher than 8 cm. Increasing pool thickness results in convective movements inside the pool. Tests (Ref. 2) demonstrated these movements negligible up to 30 cm thickness and the model does not take them into account. For deeper pools, it should be not. Furthermore the formation of the oxide layer should be different.

The development of the fire above the whole pool area is largely unknown over large surfaces. Experimental results are needed in this field. By now, wrong conclusions arise from large spills : due to large combustion area and to large quantities of sodium, even in a ventilated cell, the fire may be calculated to die before all the sodium leaks.

Part of the ESMERALDA program is devoted to answer the above questions. The two tests already performed are concerning :

- large cell volume,
- near boiling point pool temperature.

1.6 Volume effect

Two similar tests were conducted : the first in a 400 m^3 (3) caisson and the second in a 3600 m^3 concrete cell (table II). Both rooms were closed and the fire allowed to develop until self exhaustion. According to convective heat transfer laws (Sh number), the ratios M/S (sodium mass versus pool area) and V/M (cell volume versus sodium mass) were almost the same, initial pool temperature too ; one should expect similar results.

Larger than predicted values (fig. 3a, 3b) were measured in the 3600 m^3 cell (amount of burned sodium, fire duration, gas mean temperature and over-pressure). In the early stage of the fire, the agreement was good concerning overpressure and gas temperature, and, concerning the mean pool temperature during all the fire. The transient pressure rise in the last part of the fire was more clearly observed in the larger fire. The subsequent burning rate is calculated around 2,5 times higher than the instantaneous burning rate.

Operating conditions of the test in the 400 m^3, are in the validation range of PYROS code, and, the calculated results are in good agreement with the experimental ones Fig. (3 a, 3 b).

The computer code PYROS under estimated the consumption of oxygen in the larger fire, resulting in too small gas overpressure and temperature, and, same for all the other characteristics (pool and wall temperatures). The discrepancy comes from an under estimation of the initial vapor phase buring rate. In smaller cells, convective transfer of oxygen is corrected for a shape factor of the cell ; a flat cell lowers the burning rate.

This correction should no more be valid in the case of the large 3600 m^3 cell.

The computer code PYROS does not take into account the burning rate transient rise in the last phase of the fire.

To solve these two problems, a second recalculation was run in such a way that :

- burning rate is calculated without the corrective cell shape factor,
- burning rate is empirically increased by a factor 2.5 assuming a break of the oxide layer when an equivalent 4 cm thick is reached.

The second run values (fig. 4) are in a good agreement with the experimental ones during the first part of the fire. In the last part, increasing once a time by a large factor the burning rate results in a too sharp peak in the various parameters ; the real physical or chemical process should be smoother.

Several other tests in large cells (2000 and 3600 m^3) (table III) (3) verify that the initial burning rate does not depend on a cell shape factor. In order to determine the application range of the shape factor law, temperature atmosphere measurements provide information : usually, in large cells, two zones may be distinguished ; surrounding the pool there is a high temperature zone in which temperature gradients are large and temperature decreases from the pool to the edges of the zone, then above it, the second zone looks like a vertical column in which temperature is almost homogeneously distributed. The height of the first zone is estimated 4 to 5 m, the section arounds the pool area.

1.7 Pool temperature

The pool temperature reached during the stationary phase of the fire plays a significant role in the combustion process. For a 400 m^3 cell, even initial conditions were different, the pool temperature lies between 650 and 800°C. In the previous scale test in the 3600 m^3 cell, mean pool temperature was measured 800°C ; if more severe conditions are assumed, the boiling point may be reached and the combustion model should be no more valid. A pool fire involving 5 tons of sodium over 50 m^2 area in a closed cell with addition of fresh oxygen in order to maintain constant oxygen concentration was calculated as potentially resulting in temperature exceeding the boiling point. The test was performed in the 3600 m^3 closed cell. Oxygen feeding system failed in maintaining a 21 % constant oxygen concentration but large amounts of oxygen were added. From the test, calculations (fig. 5) were run in the case of 21 % constant oxygen concentration in a tight cell and in a vented cell.

In a tight cell, 900°C temperatures were calculated, but the pressure rise up to 2 10^3 Pa (absolute) and boiling point was not exceeded ; in a vented cell, the temperature decreases when the flow rate increases but the boiling point is never reached.

2. ATMOSPHERIC DIFFUSION

In the experimental program ESMERALDA, a category of tests was designed to study specifically the consequences of oxyde aerosols released into the environment from a sodium fire.

Several pool fires of 20 m^2 and 30 m^2 areas have been already performed on the floor of the 20 m high tower of the facility.

The aerosols were free to escape from open windows located at the top of the tower.

Mass and energy balances have been drawn, mostly by aerosol sampling and temperature measurement in order to evaluate :

- aerosol release rate from the pool,
- aerosol distribution in the tower,
- aerosol release rate through the top windows (various convective conditions of the internal atmosphere were tested by opening or not a door at the floor level),
- plume rise (various meteorological conditions were surveyed),
- aerosol distribution in the wake of the building and in the environment up to distances of about 1000 - 2000 m.

Special attention was paid to the main characteristics of the aerosols (granulometry, chemical changes to carbonate and bicarbonate, fall out rate inside the tower and in field).

A gaseous tracer (SF_6) was simultaneously released in order to be used as a reference for atmospheric diffusion of gases.

A computer code ICAIRWA was derived from existing "puff" models by taking into account the characteristics of the sodic aerosols and of the source term (erroneous assimilation as a point source, plume rise, local effects). By now, the range of meteorological conditions surveyed is not large enough to validate the code ; furthermore the in field sampling network has to be expanded to arount 4000 m distance from the source.

3. CONCLUSION

The main stages of a fire are well described by the "wick" model used in PYROS : inflamation, stationary and self-extinguishing phases are calculated by physical laws which make easy the extrapolation to much larger fires than the validation range.

However, some coefficients are difficult to evaluate accurate enough and experimental values were needed to validate the code. Concerning the estimation of the Sh number which plays an important role in the vapor phase burning process, the operatory conditions of the test may induce a system effect which hides the main process. A large fire test in a 3600 m^3 cell proved wall effect negligible in a large volume compared with the relation drawn from small cell tests.

From the large scale tests available, the PYROS validation range has been extended to cell volumes close to the real size of the facility rooms where a fire should be expected, and, to pool area as large as 50 m^2.

REFERENCE

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/2/ CASSANDRE J.C. MALET and als Nuclear Engineering and Design V68 2.2, 1981 pp 195 - 206

/3/ ESMERALDA Y. SOPHY IWGFR 20-24 nov. 78 CADARACHE, pp 122-129

DATE	CELL			PROGRAM	PARAMETER STUDIED
	Volume m^3	Na kg	Ventilation conditions		
1972	0.4	0.1	without venting		Basic studies
	4,5	15	"		inflammation
	22	10	"	EBCOS	Oxygen concentration Humidity
1973	400	up to 1000	without venting .... venting	CASSANDRE LUCIFER SATAN EFAS	pool area sodium amount Initial pool temperature catch pan venting procedures
1980		in field up to 300 kg Na		DIFNA	atmospheric diffusion
82-88	3600	1 ton 5 tons	without venting	ESM I.1 ESM I.2	Pool area
	2000	1 ton 0.75 ton 1,2 tons	natural convection	ESM VI.1 ESM VI.2 ESM VI.3	Atmospheric diffusion

TABLE I : POOL FIRE TEST PROGRAMM

		SMALL SCALE TEST	LARGE SCALE TEST	
SODIUM AMOUNT	M	115	1066	kg
POOL AREA	S	1	9	m^2
INITIAL POOL TEMPERATURE		550	525	°C
CELL VOLUME	V	400	3600	m^3
SPILL DURATION	t	2	4	mn
	M/S	115	118	$kg\ m^{-1}$
	V/M	3.48	3.37	$m^3\ kg^{-1}$
FIRE DURATION		180 ± 15	210 ± 10	mn
BURNED SODIUM		60 ± 10	70 ± 10	%

TABLE II : SCALE EFFECT

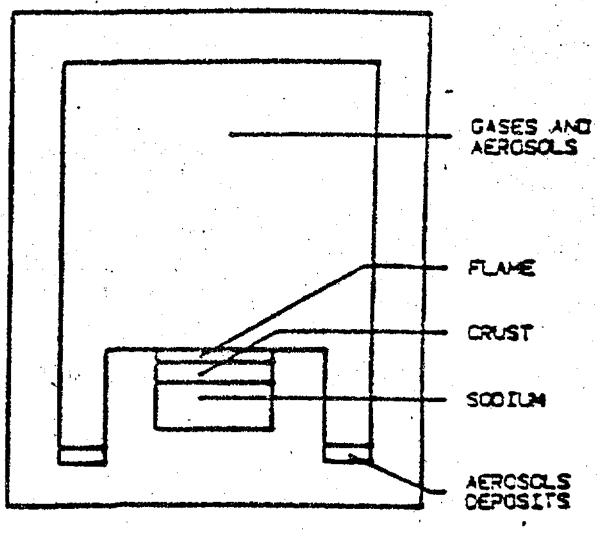


FIG 1 : PYROS MODELLING OF THE CELL

TEST	POOL			CELL		FIRE	
	INITIAL SODIUM TEMP. °C	AREA m^2	SODIUM AMOUNT kg	VOLUME m^3	VENTING SYSTEM	DURATION mn	BURNED SODIUM %
ESM I.1	525	9	1066	3600	CLOSED	210	70
ESM I.2	549	49	5000	3600	FRESH OXYGEN ADDED	1800	76
ESM VI.1	530	20	1060	2000	NATURAL CONVECTION 1 HOLE	90	95
ESM VI.2	547	20	750	2000	NATURAL CONVECTION 2 HOLES	80	95
ESM VI.3	398	30	1187	2000	NATURAL CONVECTION 2 HOLES	120	95

TABLE III - LARGE POOL FIRE TESTS ALREADY PERFORMED

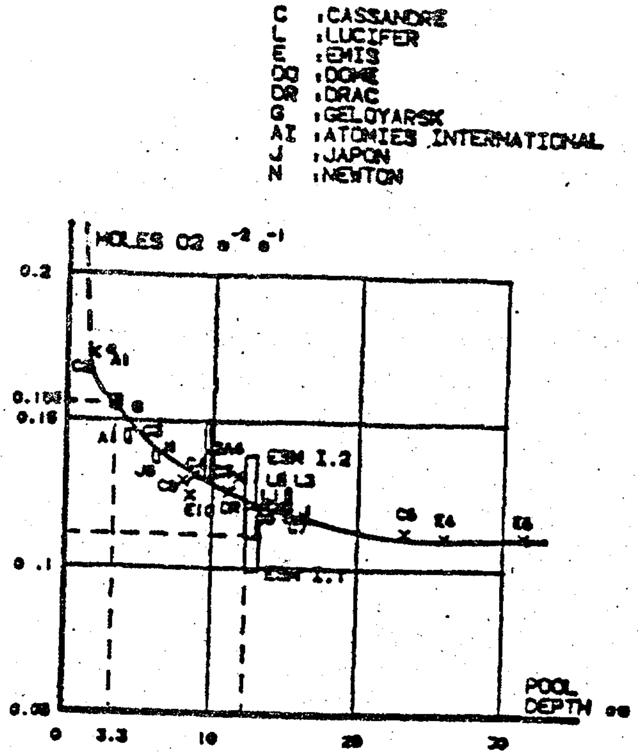
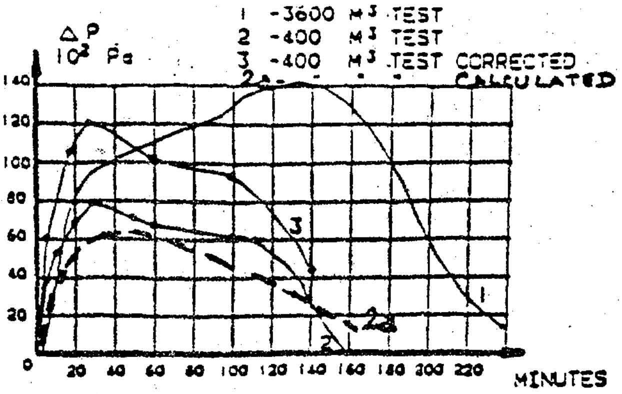
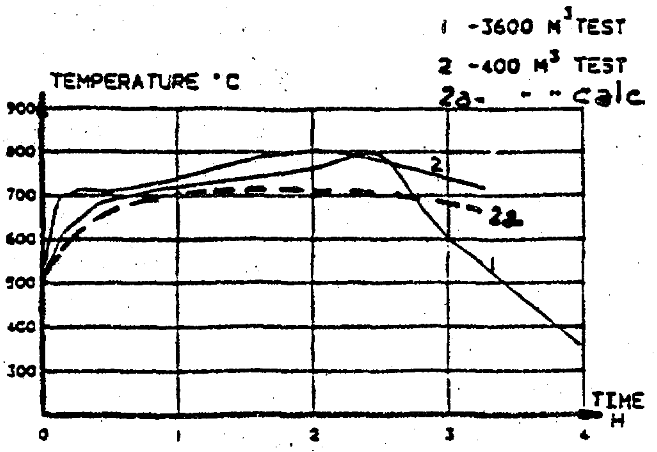


FIG 2 : INITIAL CONSUMING RATE OF OXYGEN VAPOR PHASE REACTION
CORRECTED VALUES AS 1 m² .500° C.Nu ∞



GAS OVERPRESSURE FIG : 3 a



POOL TEMPERATURE FIG :3b

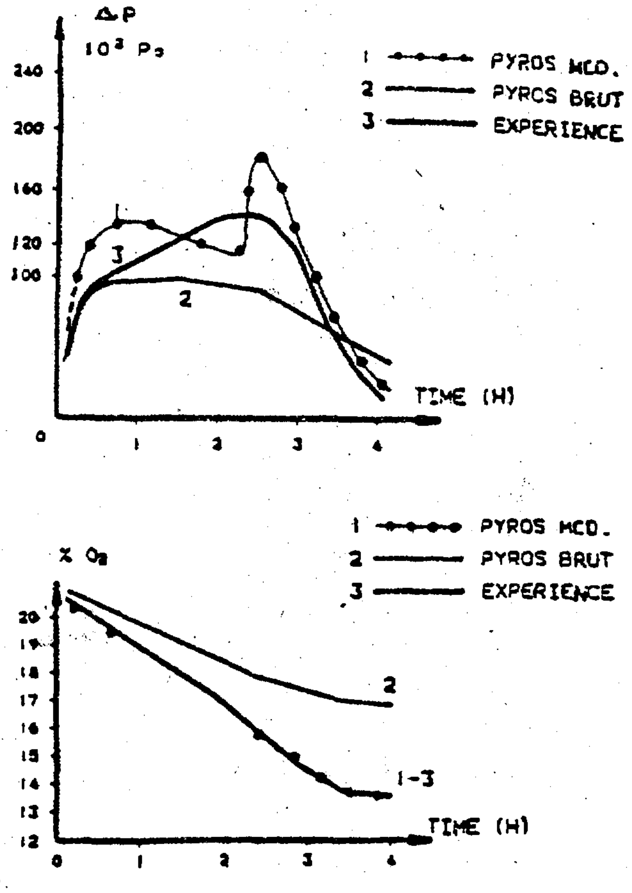


FIG 4 :CALCULATED AND EXPERIMENTAL VALUES

3600 M³.10 M² .1T

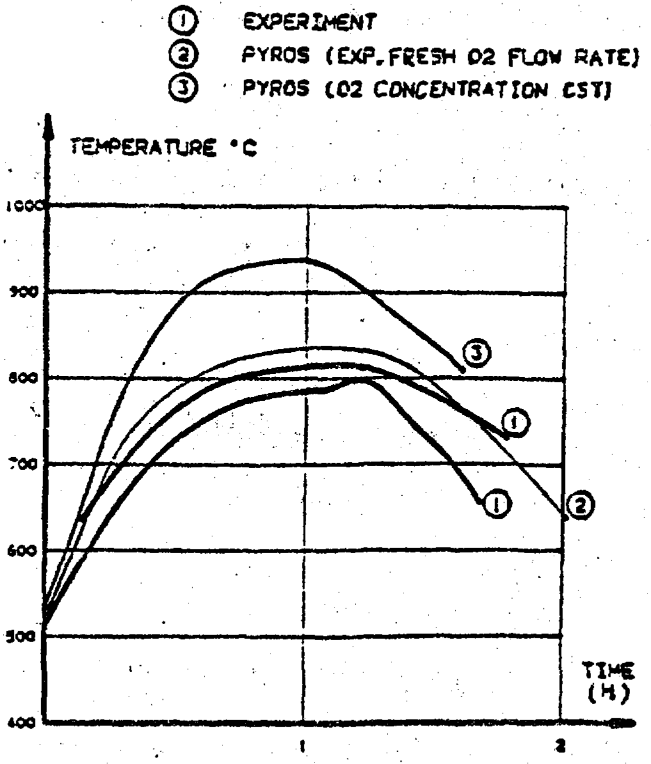


FIG 5 : CALCULATED AND EXPERIMENTAL MEAN POOL TEMPERATURE

3600M³ . 50 M² 5T