TECHNICAL COMMITTEE MEETING ON "EVALUATION OF RADIOACTIVE MATERIALS AND SODIUM FIRES IN FAST REACTORS", PNC O-ARAI ENGINEERING CENTER JAPAN 11 - 14 NOVEMBER 1996

Evaluation of the LMFBR cover gas source terme and synthesis of the associated R & D

François BALARD (CEA[1]), Bernard CARLUEC (FRAMATOME[2])

ABSTRACT

At the end of the seventies and the beginning of the eighties, there appeared a pressing need of experimental results to assess the LMFBR's safety level.

Because of the urgency, analytical studies were not systematically undertaken and maximum credible cover gas instantaneous source terms (radionucleides core release fraction) were got directly from crude out-of-pile experiment interpretations.

Two types of studies and mock-ups were undertaken depending on the timescale of the phenomena: instantaneous source terms (corresponding to an unlikely energetic core disruptive accident CDA), and delayed ones (tens of minutes to some hours).

The experiments performed in this frame are reviewed in this presentation :

1/ instantaneous source term :
- *FAUST experiments : I, Cs, UO2 source terms (FzK, Germany)*
- *FAST experiments : pool depth influence on non volatile source term (USA)*
- *CARAVELLE experiments : non volatile source term in SPX1 geometry (CEA, France)*

2/ delayed source term :
- *NALA experiments : I, Cs, Sr, UO2 source term (FzK, Germany),*
- *PAVE experiments : I source term (CEA, France),*
- *NACOWA experiments : cover gas aerosols enrichment in I and Cs (FzK, Germany)*
- *other French experiments in COPACABANA and GULLIVER facilities.*

The volatile fission products release is tightly bound to sodium evaporation and a large part of the fission products is dissolved in the liquid sodium aerosols present in the cover gas.

Thus the knowledge of the amount of aerosol release to the cover gas is important for the evaluation of the source term.

The maximum credible cover gas instantaneous source terms deduced from the experiments have led to conservative source terms to be taken into account in safety analysis. Nevertheless modelling attempts of the observed (in -pile or out-of-pile) physico-chemical phenomena have been undertaken for extrapolation to the reactor case. The main topics of this theoretical research are as follows :

- *fission products evaporation in the cover gas (FzK, Germany)*
- *sodium aerosols formation in the cover gas (UK, Japan, France)*
- *fuel degassing (Mignanelli synthesis, UK).*

(1) Commissariat à l'Energie Atomique
Cadarache DRN/DER/SERA/LEPS
13108 SAINT PAUL LEZ DURANCE
FRANCE

(2) FRAMATOME Direction NOVATOME
10, rue Juliette-Récamier
69006 LYON
FRANCE
Tel. : (33) 4 72 74 70 66
Fax : (33) 4 72 74 73 30

1 INTRODUCTION

For the safety analysis of an unlikely LMR Core Disruptive Accident (CDA), the estimation of the cover gas contamination is a very important topic.

The fission gas release to the cover gas is quite total and for this reason does not need more precise studies, while the volatile species released fraction to the cover gas depends on the physico-chemical species properties and on the thermodynamic conditions evolution during the development of the accident.

Despite the phenomena complexity, the volatile species released fraction must be determined as accurately as possible because the volatile species carry an important decay power fraction (23 % of the total decay power one second after the neutronic power loss). Besides the volatile species involve a severe biological hazard, especially Iodine and Cesium.

The non volatile species released fraction is closely bound to the molten Fuel-Coolant-Interaction (FCI) and then to the coolant decontamination factor depending on many parameters such as bubbles formation and evolution, pool depth, etc ...

At the end of the seventies and the beginning of the eighties, there appeared a pressing need of experimental results to assess the LMRs' safety level. Because of the urgency, analytical studies were not systematically undertaken and maximum credible cover gas instantaneous source terms (radionucleides core release fraction) were obtained directly from crude out-of-pile experiment interpretations.

Two types of studies and mock-ups were undertaken depending on the time scale of the phenomena: instantaneous source term (corresponding to an unlikely energetic CDA) or delayed source term.

The experiments performed in this frame are reviewed in this presentation and their results are discussed.

2. EXPERIMENTS

2.1 Case of instantaneous source term:

An energetic C.D.A results in an expanding bubble of liquid and vapour core materials (fuel, steel) mixed with sodium: the most important phenomenon from the source term point of view. The quasi-instantaneous mixing of the cover gas with the contaminated sodium nearby the bubble is caused by the very quick bubble expansion. If the CDA is stongly energetic, this expansion induces a series of impacts between the uprising sodium pool surface and the primary vessel roof. The sodium impact of the roof is followed by decreasing sodium level oscillations lasting some tens of milliseconds.

Sodium aerosols containing the main part of the volatile radionucleides are produced during these impacts. The resulting cover gas contamination by the fission gas and by contaminated sodium aerosols is called "instantaneous source term".

Starting from the "instantaneous source term", the cover gas decontamination circuit radioactive evolution can be calculated using the CONTAIN-LMR code (improvements in progress at CEA/DRN). In the same way, the source term delivered to the secondary enclosure through the roof can be calculated using the FUITE code (FRANCE) and then the CONTAIN-LMR code.

2.1.1 FAUST experimental program (FzK - Germany) [1]

The first experiments were designed in the frame of the SNR2 safety analysis.

A series of simulation tests has been performed beforehand using the sudden discharge of a gas-particle mixture into a water pool within the FAUST 2A facility. These tests were mainly used to check the design of the following facility : in the FAUST 2B facility, the water pool has been replaced by a sodium pool.

a/ FAUST 2B facility (Fig. 1 and 2)

The main components of the vessel are as follows :

- A burst disc simulating the core,
- A sodium storage tank,
- A safety buffer tank.

The main characteristics of the vessel are as follows :

- diameter 0.6 m,
- height 1.1 m,
- volume 300 liters,
- highest sodium temperature 600° Celsius,
- vessel withstanding a pressure of 1.6 Mpa,
- a cylindrical container (volume 1.5 liter) delivering gas and fission products to the sodium pool can be pressurized up to 4 Mpa.

The disc bursts by increasing the argon pressure withing the container. The vessel roof is equipped with four pneumatic valves. The cover gas sodium aerosol mixture can flow into the sample pots through these valves. Vacuum is obtained in these 7.5 liters pots before sampling. When the disc bursts, the pressure is recorded in the container, under the vessel roof and at the bottom of the vessel.

b/ FAUST2B tests

14 tests have been performed using UO2, SrO, NaI, CsI, I2 and Cs. The first four materials are solid (powder), I2 is a vapour and Cs is liquid.

A first sample is taken immediately before the burst from the cover gas to determine the background noise (in fact the detection limits of the chemical quantitative analysis of Sr, I and Cs). To get the second sample, the second valve is opened immediately after the discharge and remains open within one minute. This sample contains the materials representing the instantaneous source term.

The third and the fourth samples are taken later to get informations on the mean time source term and on the long time one.

The chemical analysis results have been managed in a manner leading to a conservative evaluation of the source terms.

c/ FAUST 2B results

- Sodium aerosols:

After the disc rupture, the sodium aerosols concentration is to be found between two extreme values :

- 0.2 g Na/m^3 at low temperature for a 1 Mpa burst pressure,
- 360 g Na/m^3 at high temperature for a 4 Mpa burst pressure.

The average value 53 g Na/m^3 is a very high value decreasing quickly with time.

- Fission products and uranium oxyde:

The realistic instantaneous source term deduced from the FAUST 2B experiments can be seen on the table below :

	Xe, Kr	I, Br	Cs	Te	SrO	UO2
FAUST2B	1	0.1	1.0E-4	"	1.0E-4	1.0E-4

On the mean time, the I and Cs source terms trend towards increase.

This tendancy is confirmed by the later FAUST 3 experimental results. This experimental program was more representative because Iodine and Cesium were scattered within an UO2 matrix which is vaporized by a huge, sudden condenser discharge within the sodium pool. But because lack of funding, these FAUST 3 more realistic experimental results have not been yet interpreted.

2.1.2 FAST experimental program (USA) [2]

In the FAST facility the bubble is produced by UO2 vaporization. The fission products behaviour has unfortunately not been studied.

a/ FAST facility (Fig. 3)

The FAST facility consists of a vessel with a roof and is equipped with command and measurement devices.

The main vessel characteristics are as follows :

- volume 0.46 m^3,
- height 1.83 m,
- external diameter 0.61 m,
- the walls are made of stainless steel 304 H, 22 mm thick and are designed to withstand a 3.08 Mpa pressure,
- electrical resistances able to sustain a 800 K sodium temperature are supported by the walls.

The vaporization device is made up by sample holders, an UO2 sample and two Tungstene electrodes. The sample is made of 13 UO2 pellets weighing 17.3 g. The pellets are wrapped by UO2 microspheres insulating the pellet pile. The volume between the tubes and the microspheres is pressurized by Xenon simulating the fission gas.

The steel tube is engraved axially and circumferentially to get an homogeneous rupture.

b/ Operating the FAST facility

The simulation of a CDA has been simulated in the following manner : the UO2 samples wrapped by a Xenon atmosphere are immersed in a sodium pool. Then, Joule effect is used to heat the sample in two phases : first the sample gets molten by an electrical power generator and then is vaporized by condensers discharge (10 MW lasting some milliseconds).

During the sample dislocation, UO2 is condensed (and rapidly frozen in particles) into aerosols within the bubble.
So, the bubble content is made of Xenon mixed with UO2 particles.

The aerosols transport through the pool and their release to the cover gas are dependent of the bubble pool interaction dynamics.

The bubble radii and the pool behaviour have been estimated by pressure measurements within the sodium pool and in the cover gas. The produced aerosol mass is determined by cover gas analysis.

c/ FAST results

About ten samples have been vaporized, nine among them have burst in sodium at depths varying between 30 and 1060 mm.

The aerosol released mass is very small and the release is very sensitive to the immersion depth. The aerosol release depends on the bubble kinetics and dynamics, and three reasons for the small release have been identified :

- in each experiment, the bubble mean diameter remains smaller than the immersion depth,

- aerosols included in the oscillating bubble remain immersed in sodium,

- the bubble life duration is smaller than the time needed by the sodium pool uprising (because fast cooling and collapse of the bubble).

The results concerning the aerosols release to the cover gas are summarized on the Figure 4.

2.1.3 CARAVELLE experimental program (CEA - France) [1]

These experiments have been performed in a vessel representing the Super Phenix 1 primary vessel and its internal structures.

The goal of the CARAVELLE experiments was to study the aerosols transport to the cover gas, the sodium leak to the roof and the influence of the internal vessel structures. They were more representative of a low-energetic CDA.

a/ CARAVELLE facility

In the CARAVELLE facility, sodium is simulated by water and UO2 particles by bronze particles.

Hot water is heated within a spherical glass container set inside a concentric spherical glass wrapping. The volume between to two containers is pressurized with permanent gas.

A known quantity of bronze particles (diameter varying from 40 to 150 micrometers) was previously added to hot water. As the water temperature increases, the pressure increases and then the container bursts inducing the release in the water plenum of gas bubbles carrying bronze particles.

b/ CARAVELLE results

Starting from 50 g of bronze particles in the containers, 1.5 mg only have been collected in the cover gas. A release fraction of 3.0E-5 could be estimated.

In the CARAVELLE case, the particles are transported to the cover gas by the slow (between 0.2 and 5s.) rising of very small bubbles.

The ratio of particles transferred to the cover gas increased counterwise their diameter : more than 93% for a 25 µm diameter and 8 % for a 34 µm diameter.

2.2 Case of delayed source term:

Other kinds of severe accident without energetic consequences result in a more or less important core melting. For instance an Unprotected Loss of Heat Sink can result in a significant fission product release to the cover gas on the long time. Moreover, on the long term of an energetic CDA, other phenomena than those presented in § 2.1 may play a role.

Owing to the temperature gradient existing in the cover gas between the sodium pool surface and the roof, the sodium pool evaporates and the sodium vapour condenses mainly on liquid sodium aerosols.

The volatile fission products release is tightly bound to sodium evaporation and a large part of the fission products is dissolved in the liquid sodium aerosols present in the cover gas.

2.2.1 NALA 2 experimental program (FzK - Germany) [1]

This experimental programme has been undertaken in the frame of the SNR 300 core-catcher studies. It concerned the UO2 and PF release and sodium evaporation velocities.

All the tests have been performed in an inert atmosphere. In other words, no research has been undertaken concerning the contamination created by sodium fires.

a/ NALA 2 facility (Figure 5)

The main characteristics of the facility are as follows :

- a heated vessel whose volume is 2.2 m3,
- a pot filled with sodium (26 cm inner diameter),

- an inert gas feeding,
- safety systems,
- aerosols measurement devices.

The vessel is filled with argon (1 bar pressure) and heated up to 400 K. This temperature is kept constant during the whole experiment.

The pot filled with 1 Kg of sodium is heated at the wished temperature between 700 K and 1000 K. The plateau temperature is reached and maintained by flame regulation.

The external heating duration (up to 3 hours) is driven by the evaporation velocity in such a manner that 10 % of the sodium pool evaporates.

Six thermocouples are placed in the vessel and two in the sodium pool.

The gas temperature remains constant during the whole experiment. A large quantity of aerosols has been observed nearby the pool surface.

Owing to the aerosols condensation and deposition, very small sodium droplets appear on the vessel walls.

The sodium evaporated mass can be measured at the end of the experiment because the vessel is totally closed.

Thus informations on the sodium evaporation velocity can be got from each experiment, assuming a constant velocity.

b/ NALA2 tests

The main parameters governing the sodium pool retention capacity is sodium pool temperature.

A quantitative estimation of the enrichment factors was got from the NALA experiments (**the enrichment factor** is defined as the ratio of the radionucleide concentration in the released sodium to its concentration in the pool).

The studied radionucleides are :

U, Cs, I, Sr

c/ NALA2 results

Except for Cesium, the radionucleides sodium pool concentration can be approximately considered as constant during the experiment (duration about some ten minutes).

The enrichment factors got from the experiments are as follows (sodium pool temperature: 500°C) :

Cs > 1.	I ~ 0.33	Sr ~ 1.4E-3	U ~ 2.5E-4 to 1.0E-3

Cs and I are released by evaporation, SrO and UO2 (non volatile species) release is driven by sodium evaporation velocity and depends on many parameters, mainly on particles sizes.

2.2.2 PAVE experimental program (CEA - France) [3]

4.4 Kg of sodium containing 47.5 mCi Iodine without stable isotope, were heated up to 700 or 740°Celsius during 15 minutes. 0.35 Kg of sodium aerosols were released containing 3.2 mCi of Iodine.

Thus one can deduce the Iodine enrichment factor : 0.32 (nearby the NALA value).

Experiments were also performed with UO2. For UO2, the results do not agree between the both experiments (PAVE and NALA) but they were not performed with the same boundary conditions. Nevertheless the orders of magnitude of the UO2 enrichment factors are about the same.

2.2.3 NACOWA experimental program (FzK - Germany)

Getting input data for the EFR cover gas and roof design and giving enrichment factors for source terms estimate was the goal of the NACOWA experiments.

In the frame of the NACOWA tests the following items have been approached :

- sodium mass concentration in the cover gas,
- sodium aerosols sizes,
- whole heat transfer through the cover gas,
- radiative heat transfer through the cover gas,
- sodium deposition on the roof,
- temperature profile through the cover gas,
- helium as cover gas instead of argon,
- aerosols Cesium enrichment,
- aerosols Iodine enrichment.

The sodium pool temperature and the cover gas height were the main parameters. Other parameters varied such as roof temperature and fission products concentration in the pool.

a/ Operating the NACOWA facility

The NACOWA facility was the result of the FAUST facility modification.

The operating characteristics were as follows :
- sodium pool volume 228 liters,
- *pool temperature 500°Celsius*,
- roof temperature 120°Celsius,
- cover gas height between 12.5 and 33 cm.

The above conditions were standard one and could be modified :

- pool temperature between 270 and 545° Celsius,
- roof temperature between 100 and 300° Celsius,
- cover gas height can be larger.

Several Cesium and Iodine contamination levels were used to study the influence on enrichment factors.

b/ NACOWA results

- Sodium aerosols:

With a low roof temperature, aerosols appeared when the pool temperature is about 350° Celsius. The concentration increased thoroughly with the pool temperature : aerosols concentration 36 g Na/m3 for a pool temperature of 565°C. The roof temperature (and particularly the gradient between pool surface and roof) influenced the aerosols mass concentration : for instance, sodium mass concentration 5 g Na/m3 for a roof temperature 420°Celsius, and a pool temperature 500°Celsius.

- Fission products enrichment:

On the long time the enrichment factor is governed by a distillation process. The Cesium enrichment factors were measured between 7 and 20. Maximum Iodine enrichment factors exceeding 700 were measured in the cover gas.

If argon is replaced by helium, sodium evaporation velocity and enrichment factors are lower.

2.2.4 Other French experiments (CEA - France) [4]

French experiments on sodium aerosols concentration have used facilities with pool diameters around ten times larger than the NACOWA one.

The experimental results got from the COPACABANA facility (2 m vessel diameter) and from the GULLIVER facility (6 m vessel diameter) were as follows :

- liquid sodium aerosols concentration increases with sodium pool temperature,
- liquid sodium aerosols concentration increases with the temperature gradient between the pool surface and the roof,
- liquid sodium aerosols concentration increases also if the cover gas is swept by a cool gas steam.

A good agreement exists between these last results and the NACOWA one.

2.2.5 In-pile fission product release fraction [5]

The experimental release fraction values (known as RBCB one) are issued from the analysis of simple pin ruptures under normal and accidental running in the PFR, Phenix and KNK2 reactors. They are reported in the first column of the table below (no indication is given concerning the observation time).

The SCARABEE reactor experimental results (in-pile cluster tests) stem from post-mortem fuel analyses and thus a delayed source term can only be deduced. Nevertheless these results are got with geometry and boundary conditions different from those of a pool reactor.

On the table below are given in addition the MOL7C and CABRI experimental results :

Radionuclide	Release Fractions			
	RBCB	SCARABEE	Mol/7C	CABRI
Xe	1.0 [a]	1.0	1.0	1.0[b]
Cs	0.7	0.25	0.21	1.0[b]
Te/Sb	0.2	0.06	0.03	-
I	0.3	-	0.08	-
Fuel	#	-	-	-

a : fission gas release in the cover gas
b : released from molten fuel.

3. REACTOR ESTIMATED SOURCE TERMS

For the instantaneous source term, the experimental results are generally given as enrichment factor of the cover gas or (reverse value) as retention factor of the sodium pool. The enrichment factor measurements, combined with the approximatively measured mass balance between the cover gas and the sodium pool, enable the calculation of a conservative "instantaneous source term" in the reactor case.
For volatile Fission Products, the Iodine and Cesium vapour contributions to the source term are negligible compared to the Iodine and Cesium combined with liquid sodium aerosols contribution.
For non volatile radionuclides, the enrichment factors depend on the pool height above the core, on the obstacles present in the plenum, and mainly on the particles size spectrum.

The conservative "instantaneous source term" values, given for several reactors in the table below, are the results of the available experimental research at the time of the evaluation and of a consensus within every country:

	Germany SNR300** (Na 500°C)	EFR*	MONJU**	SPX1**
Xe, Kr	1	1	1	1
I, Br	0.5	0.1	0.1	$5.0\ 10^{-9}$
Cs	0.5	0.1	0.1	$5.0\ 10^{-5}$
Te	0.5	0.1*	0.1	$4.0\ 10^{-7}$
SrO	$1.7\ 10^{-2}$			$3.0\ 10^{-3}$
UO2	$1.7\ 10^{-2}$	10^{-4}	$2.0\ 10^{-3}$	$3.0\ 10^{-3}$

* non energetic CDA.
** energetic CDA.

For the delayed source term, the volatile fission products release is tightly bound to sodium evaporation and a large part of them remains dissolved in the liquid sodium aerosols. This release trends towards increase with time. On the long time (i.e more than some tens of minutes), a steady-state distillation settles as the cover gas contamination (I and Cs) reaches a high asymptotic value.

The non volatile radionucleides release is sensitive to sodium evaporation velocity and depends on many parameters, mainly on the particles size spectrum.

4. MODELS AND CODES

Attempts have been undertaken to predict the radiological cover gas accident evolution after a core melting accident.

Most of the theoretical studies (REVOLS Mod2 code models) have been performed in Germany, in relation with the experimental programs.

4.1 Sodium evaporation velocity:

The sodium evaporation velocity has been studied, using the NALA experimental results.

The evaporating sodium mass flow can be approximatively represented by the simple formula :

m [kg $Na/m^2/h$] = 0.1*p [torr]

where p is the sodium pressure vapour above the sodium pool surface.

The above formula has no predictive value, but on the basis of the NALA experiments, another model able to predict the sodium release velocity has been built by FZK and the Bochum University (Germany) [6].

This model is now available within the last CONTAIN-LMR/1B Mod1 working version (basis SNL version modified by FZK).

4.2 Cesium release:

Cesium enrichment of the released sodium has always been observed in the NALA experiments.
The total amount of released sodium depends on the test duration and on the sweeping velocity in the vessel.

The basis of the proposed calculation model is as follows :

- Na and Cs evaporation velocities are proportional to their own vapour pressure.
- Cesium is homogeneously dissolved in Sodium.
- the whole release velocity is proportional to the pool area.

This model is integrated in the REVOLS Mode 2 code.

If specific sodium release velocities are got from the experiments, the release can be taken into account in the temperature increase and decrease phases.

On the Figure 6, a good agreement was got between the experimental values and the calculated ones.
In this case, the data concerning the enrichment factors are relatively meaningless because the enrichment factors vary thoroughly with time.
A chemical retention factor by other fission products is possible (i.e. with Iodine) The fission products interactions in liquid sodium have not been yet investigated.

4.3 Iodine release:

The Rayleigh's distillation formula is used as basis relationship.

The activity coefficient of Iodine in infinitesimal dilution in sodium is taken into account to calculate the real sodium iodide vapour pressure. The sodium vapour pressure evolution versus temperature is also taken into account.

The equation solution mode is iterative.

This model is integrated in the REVOLS Mode 2 code.

4.4 Sodium aerosols formation in the cover gas [7, 10, 11, 12]:

At the beginning of the programme (1987), the NACOWA experimental programme (Germany) was devoted to the development of the German code GASMO in the frame of the SNR2 studies. Later the NACOWA programme supported the CGAS code development in the frame of the EFR studies. At the end of 1993, the programme was stopped because lack of funding.

An important theoretical work concerning the cover gas, especially aerosols formation and behaviour has been performed in the UK and in Japan (1991) [8,9].

4.5 Fuel degassing [13]:

Fuel degassing is an important item because the Fission Products degassing velocity influences directly the unsteady state development of the short time source term in the cover gas.

If an energetic core disruptive accident is assumed, the order of magnitude of the fission products release duration from a fuel undergoing an extremely high heating velocity is not well known.
The most important fission product is Cesium, owing to its relative abundance in a high burn-up fuel after fission gas release. In the codes describing an energetic CDA, only the fission gas contained in the liquid fuel are taken into account, and Cesium release is considered as a calculation parameter.

If no high and sudden energy release is assumed, the fission products release velocity is an important item. There is no quick initial fission products release by the fuel. Very few models are available.

For the two types of scenarios above, using a lot of experimental results and publications, the Mignanelli's synthesis (UK) leads to the following consideration. For a given fission product, the release factor versus time is given by the relationship :

$$F = 1. - \exp(- \text{alfa} * A * t)$$

where: alfa(min.) is the release constant,
A (cm^2) is the fuel surface exchanging with sodium,
t (min.) the contact duration.

The recommended fission products constant release values for EFR fuel are gathered below:

Fission Product	Release Constant (min^{-1})			
	1800°C[a]	2100°C[a]	2500°C[a]	2800°C[b]
Xe, Kr	1.0	1.0	1.0	1.0
Cs, Rb	0.57	1.0	1.0	1.0
I, Br	0.57	1.0	1.0	1.0
Te, Se	1.9E-02	2.6E-02	7.2E-02	1.0
Sb	2.8E-03	4.0E-03	7.2E-02	1.0
Ba, Sr	-	-	1.3E-03	2.1E-02
Mo, Tc	2.3E-03	2.6-03	3.0E-03	3.3E-03
Ru, Rh, Pd	-	-	2.3E-04	3.0E-03
Rare earths[c]	-	-	6.0E-05	1.6E-03
Ce	-	-	6.0E-05	9.0E-04
Zr	-	-	2.2E-05	8.7E-04

[a] Based on Gittus recommendations
[b] Based on Parker
[c] Obtained from WASH 1400 assessment

One can note that for interaction between molten fuel (2800°Celsius) and liquid sodium, fission gas and volatile fission products are immediately transferred to sodium.

The time needed by the bubbles to reach the cover gas and the resulting short time source term composition depend on the mechanical and physico-chemical behaviour of the bubbles in the sodium pool.

Research is now in progress in PNC concerning this item (TRACER code).

5. CONCLUSION

An important amount of work was performed on the LMR source term in the past, but slowed down or stopped in the 5 last years, except in Japan. This paper presents the synthesis of this work, for the instantaneous and delayed source terms in the cover gas: experiments and models.

Then the reactor cover gas instantaneous source terms used in the past are presented for different reactors. Most of them are likely conservative. Accounting for the experimental and theoretical results accumulated since their evaluation should allow to propose more realistic values in the future, both for instantaneous and delayed source terms.

To improve this evaluation, the main R&D needs are the following ones :

- modelling of the physico-chemical phenomena (undertaken in the TRACER code of PNC),
- experimental complements on physico-chemical interactions of FP dissolved in the sodium (NaI, CsI, Ni, Cs) which could influence the NaI and Cs vapour pressure in the cover gas and thus their release fraction.

REFERENCES

1. « Experiments on liquid-metal fast breeder reactor aerosol source terms after severe accidents »
G.BERTHOUD (CEA), A.W.LONGEST (ORNL), W.P.SCHUTZ (FzK)
Nuclear Technology Vol.81 May 1988 pp.257 to 277

2. « LMFBR source term experiments in the Fuel Aerosol Simulant Test (FAST) facility »
J.C.PETRYKOWSKI, A.W.LONGEST, A.L.WRIGHT (ORNL)
Fast Reactor Safety: Proc. of the Int. Topical Meeting, Knoxville, 21-24/04/1985.

3. « Evaluation of the sodium retention factors for sodium products and fuel »
M.BERLIN, E.DE MONTAIGNAC, J.DUFRESNE, G.GEISSE (CEA)
Int. Meeting on LMFBR safety and related design and operational aspects, Lyon (France), July 1982.

4. « Transport of sodium through the cover gas of a sodium cooled fast reactor »
C.F.CLEMENT, P.HAWTIN
Proc. of Int. Conf. on liquid metal technology in energy production,Seven Springs, Pennsylvania (1976), pp. 603 to 609.

5. « Primary containment source term analysis for CDFR. Hypothetical core disruptive accidents »
N.J.HOLLOWAY, G.J.VAUGHAN, M.MIGNANELLI, J.HARDING, P.E.POTTER (UK)
Proceedings of the conference of Guernesey (1986), session 1, pp. 103 to 106.

6. « A mechanistic model for the prediction of sodium release from a liquid pool in an inert atmosphere gas »
U.BROCKMEIER, M.KOCH, H.UNGER (FzK)
International Fast Reactor Safety Meeting, 1990, Vol.1, Session 3, pp. 307 to 318.

7. « Aerosol formation from heat and mass transfer in vapour gas mixtures »
C.F.CLEMENT
Proc. Royal Society A398 (1985), pp. 307 to 339.

8. « Sodium aerosol formation and removal mechanisms in the fast reactor cover gas space »
I.J.FORD
Journal Aerosol Science Vol.24 (1993), N°2, pp. 237 to 253.

9. « Analytical study on mass concentration and particle size distribution of sodium mist in cover gas phase of LMFBR reactor vessel »
H.YAMAMOTO, T.SAKAI, N.MURAKAMI
Journal Aerosol Science Vol.22 Suppl. 1 (1991), pp. S713 to S716.

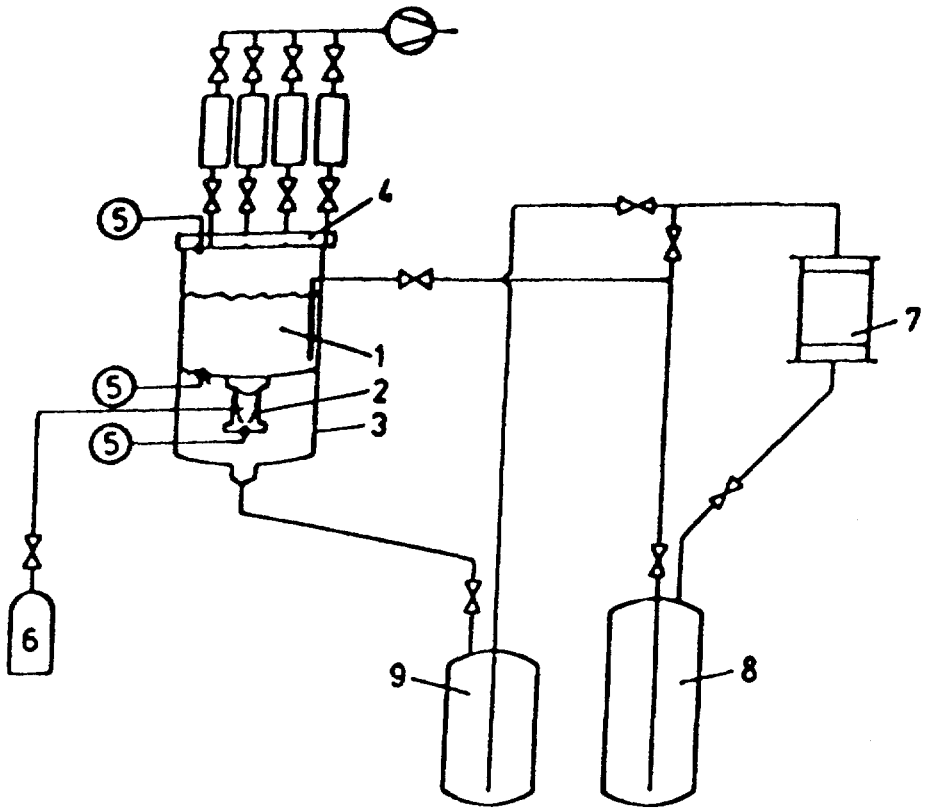
10. « Sodium aerosol development in an argon cover gas »
M.JULIEN-DOLIAS (CEA)
Proc. of the 4th. Int. Conf. on liquid metal engineering and technology, Avignon (France), Oct. 1988, pp. 113.1 to 113.11.

11. « Radiation heat transfer through the gas of sodium cooled fast breeder reactor »
P.PRADEL, S.FRACHET, D.PETIT
Proc. of the 3rd. Int. Conf. on liquid metal engineering and technology, Oxford, April 1984, Vol.1, pp. 459 to 462.

12. « Prediction of coupled heat and mass transfer in the fast reactor cover gas: the CGAS code »
Y.L.SINAI, I.J.FORD, J.C.BARRETT, C.F.CLEMENT
Nuclear Engineering Design 140 (1993), pp. 159 to 193.

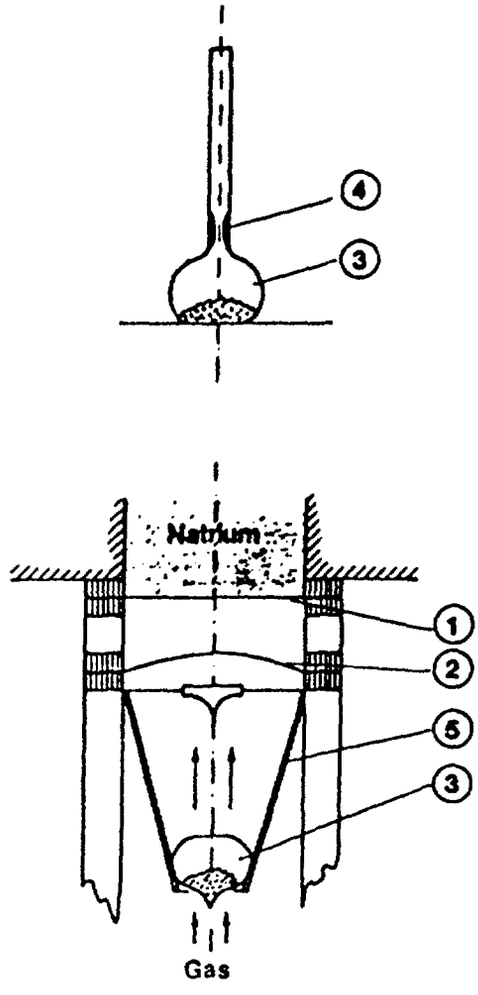
13. « European programme on source term evaluation following a CDA »
M.A.MIGNANELLI
USA-Europe exchange Meeting N°3 on safety topics.

Figure 1: FAUST2B facility



1- Containment (0.6 m diameter; 1.1 m high) loaded with sodium
2- Source tank (1450.cm3) with inconel burst disk (4 MPa)
3- Safety bell
4- Deck with pneumatic valves and sampling tank
5- Pressure gauge
6- Argon feeding
7- Sodium melting facility
8- 500. liter storage tank
9- Safety tank

Figure 2: FAUST2B facility Fission Product source



1- *Stainless steel sheet*
2- *Inconel burst disk*
3- Glass bulb filled with Cs or I2
4- Obturation location
5- *Bulb holding basket inside the source tank*

Figure 3: FAST facility.
Sketch of the UO2 vaporization device

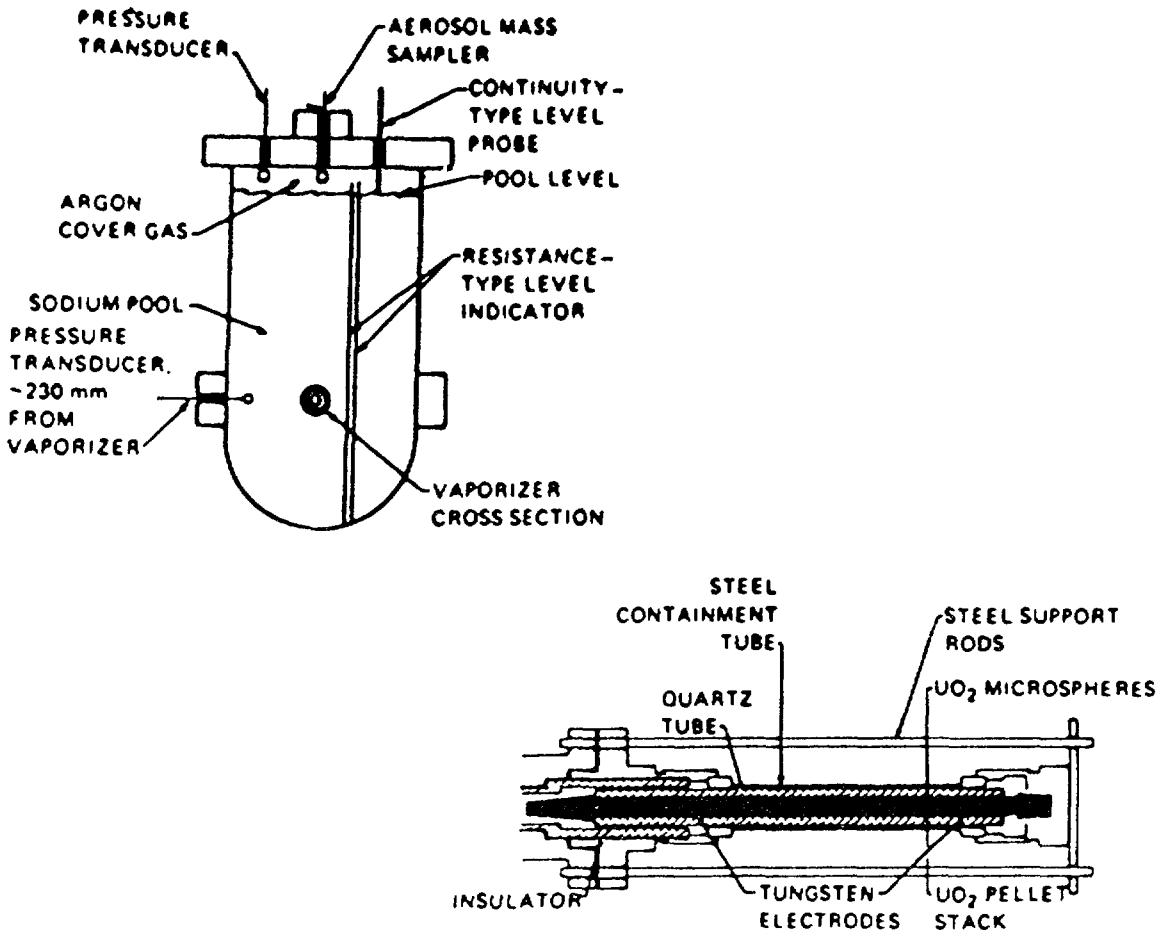


Figure 4

FAST Experiments : Measured uranium mass in the cover gas (for 17. g vaporized UO_2)

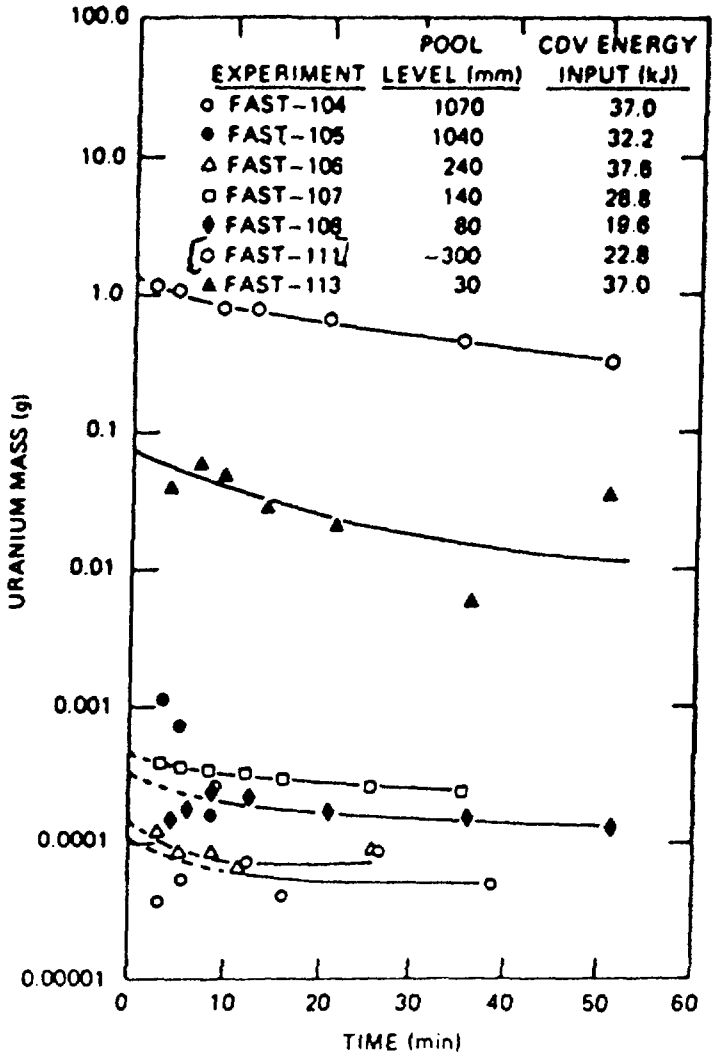
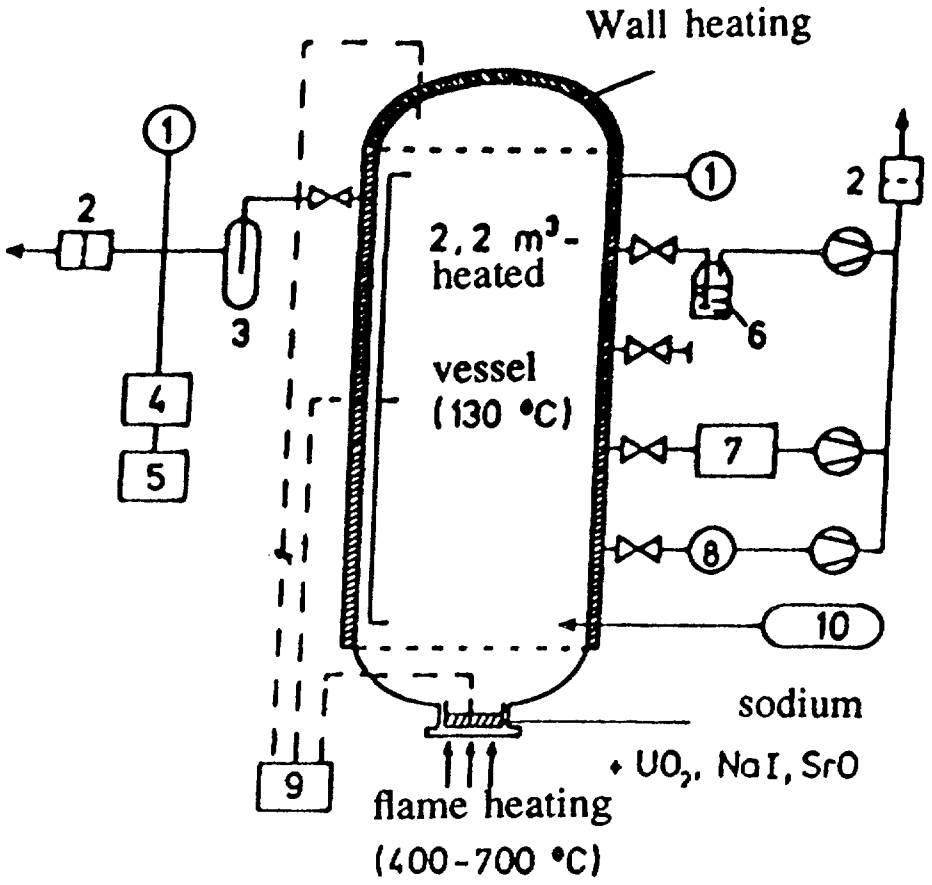


Figure 5: NALA2 facility



1- pressure measurement
2- filter
3- cold trap
4- oxigene measurement
5- hygrometer
6- scrubbing flask
7- continuous measurement of the sodium aerosols concentration
8- Andersen impactor
9 - temperature measurements (2TC in Na pool, 6TC in cover gas, 2 TC in deck)
10- argon feeding

Figure 6

Caesium sodium pool depletion during evaporation (calculated curve + exp. point at the end of test)