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May 13, 1998

MEMORANDUM TO: Michael E. Mayfield, Chief
Electrical, Materials and Mechanical Engineering Branch
Office of Nuclear Regulatory Research

Jack R. Strosnider, Jr., Deputy Director
Division of Engineering
Office of Nuclear Reactor Regulation

Joram Hopenfeld
Generic Safety Issues Branch
Division of Engineering Technology
Office of Nuclear Regulatory Research

FROM: Jocelyn A. Mitchell Jocelyn A Mitchell
Technical Assistant
Office of the Executive Director for Operations

SUBJECT: DPO REGARDING REPAIR CRITERIA FOR STEAM GENERATOR TUBES -- CSARP MEETING VIEWGRAPHS

The attached are viewgraphs from three of the presentations at the Cooperative Severe Accident Research Program meeting, which was held in Bethesda, MD, May 4-7, 1998. These presentations discussed calculations or experiments of deposition in steam generator tubes and may be germane to the issue of steam generator integrity. The three are:

(1) "Current Status of VEGA Project and Analytical Activities on Aerosol Behavior at JAERI," A. Hidaka, et al.

(2) "ASTEC integral code: Status of development and validation; First application to PHEBUS.FP," F. Jacq, et al.

(3) "Analysis of the two first PHEBUS.FP tests: fuel bundle degradation, Fission Product release, transport in the circuit and behaviour in the containment," S. Bourdon, et al.

If you need further information about any of these presentations or the underlying work, I suggest that you contact Charles Ader, Chief, Accident Evaluation Branch, Office of Nuclear Regulatory Research.

Attachment: As stated

See ACRS March 5, 1997 Meeting regarding deposits in the

Analysis of the two first PHEBUS.FP tests: fuel bundle degradation, Fission Product release, transport in the circuit and behaviour in the containment

S.Bourdon, F.Serre, M.Kissane, D.Jacquemain

IPSN/DRS/SEMAR Cadarache, France

Contents

First two PHEBUS.FP experiments

Fuel bundle degradation

FP release and transport

FP behaviour in the containment

Abstract

The analysis of the two first experiments of the international program PHEBUS.FP has been performed by IPSN using both mechanistic codes and modules of the integral source term codes, FPT0 with fresh fuel and FPT1 with irradiated fuel. These codes allow the whole range of phenomena and situations to be covered.

Bundle degradation is analyzed with the mechanistic code ICARE2 V2 mod2 :

- during the calibration phase, the bundle temperatures are correctly predicted,
- during the oxidation phase, the agreement is also correct: control rod failure, temperature escalation, total H2 production. At the end of this phase, the calculation shows low fuel dissolution by molten Zry.
- in the melt progression phase, the bundle degradation is largely underpredicted. The fuel melting temperature needs to be decreased to about 2500 K (solidus temperature) to reproduce the experimental results. Then the temperatures of the shroud in its lower part are correctly calculated, and the agreement with the post-irradiation examination is better (~3.2 kg of materials in the frozen molten pool in FPT0 and ~2 kg in FPT1).

The Fission Product release and transport in the RCS is analyzed with the following codes: ELSA (semi-empirical, ESCADRE and ASTEC module) and MFPR (mechanistic) for release from intact fuel, and SOPHAEROS (ESCADRE and ASTEC module) for FP transport. Their conclusions are:

- a suitable diffusion length in ELSA for volatile FP allows reproduction of the experimental results; but the calculated semi-volatile release is too high for both tests.
- the phenomenological sequence is correctly represented by MFPR (and consistent with ELSA) but with wrong timing; the opening of porosities is later in FPT0 compared to FPT1.
- the experimental results can be explained broadly with SOPHAEROS which produces a consistent image with candidate FP species. However, the deposition in the SG is under-estimated, perhaps due to mechanical resuspension throughout the test.

As for the containment behavior, the JERICHO (0D, ESCADRE module) and TRIO.VF (mechanistic 3D code from CEA) codes for thermalhydraulics and the IODE code for Iodine behavior were used:

- the 0D JERICHO modeling gives satisfactory results for FPT0, particularly the condensation flow rate, when using the Reynolds analogy and the Chilton-Colburn or Collier models. Complementary calculations with TRIO.VF confirm the JERICHO hypothesis of a well-mixed atmosphere and show a mixed convection flow pattern. The RALOC multi-compartment code (ASTEC module) is currently used for FPT1 analysis.
- the IODE code (ESCADRE and ASTEC module) is being improved to include the feed-back from FPT0 interpretation: for instance the importance of the Ag-I reactions in the sump.

Analysis of PHEBUS.FP has already led to improvement of models in some of the codes or to reorientation of R&D programs. The updated codes are now in use preparing the next PHEBUS.FP experiments.

PHEBUS.FP first two experiments

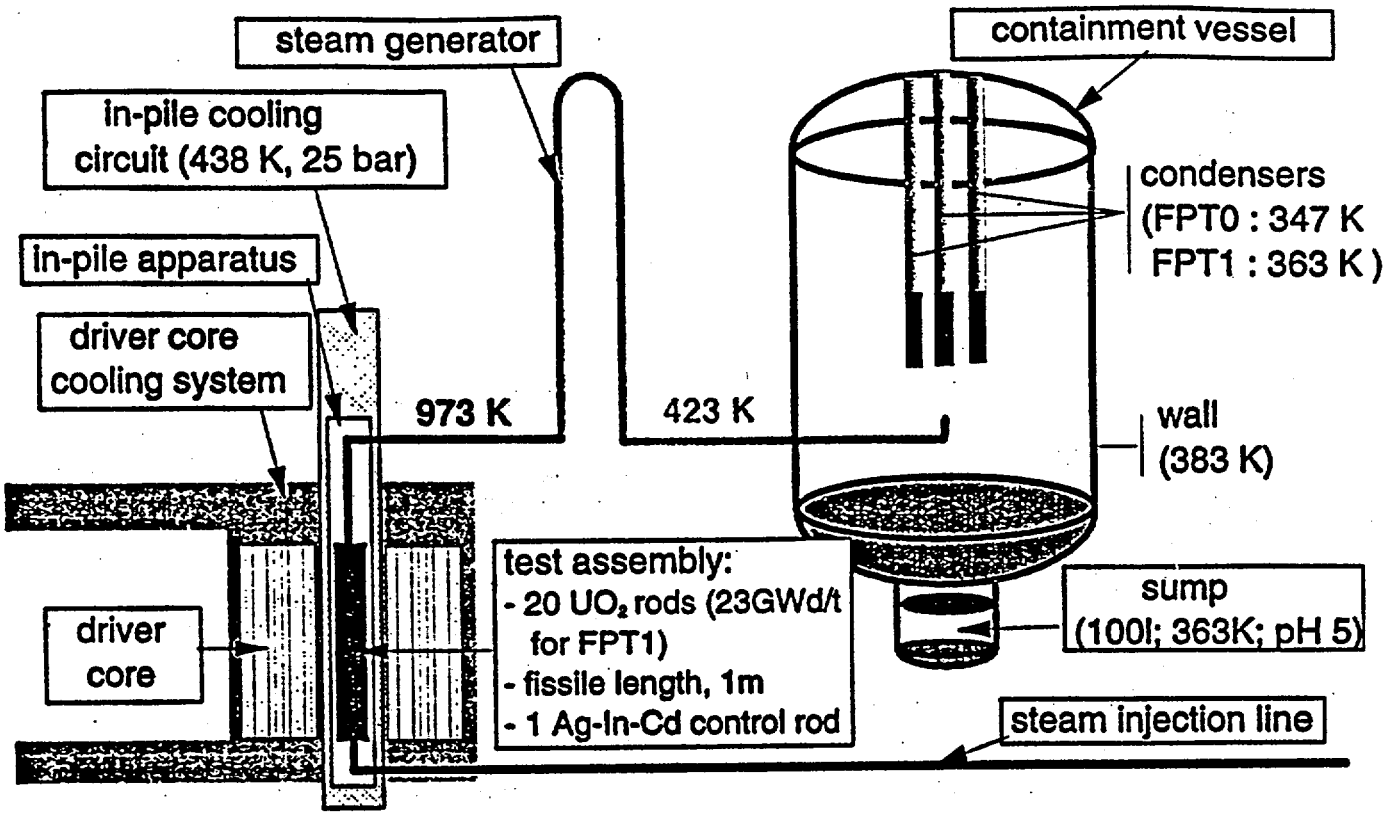
- the IPSN analysis covers the whole range of phenomena occurring in the PHEBUS.FP experiments, using mechanistic codes or modules of integral source term codes (ESCADRE, ASTEC):
  - Fuel bundle degradation (ICARE2 code)
  - FP release (ELSA and MFPR codes)
  - FP transport in the circuit (SOPHAEROS code)
  - FP behaviour in the containment: thermalhydraulics (JERICHO, TRIO.VF codes) and Iodine (IODE code).

☛ *see also the CSARP paper on the ASTEC code which includes preliminary applications of coupled codes to PHEBUS.FP.*

- Two integral experiments performed in PHEBUS.FP:
  - FPT0: end of 1993, fresh fuel,
  - FPT1: end of 1996, irradiated fuel

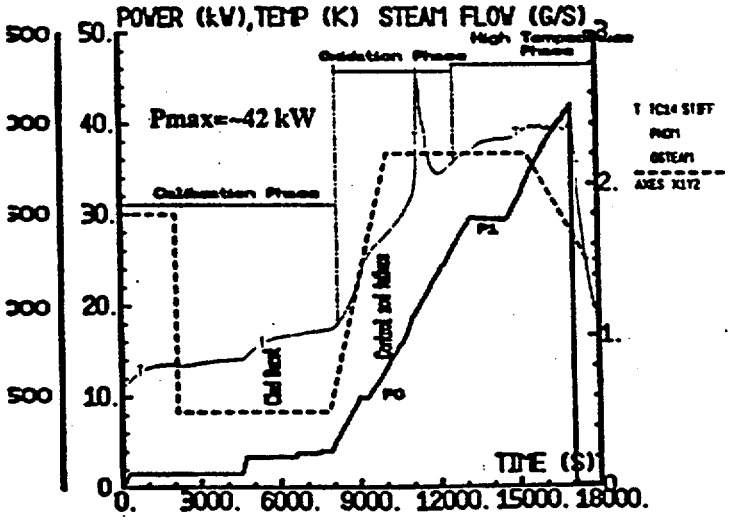
Schematic presentation of the circuits

PWR => Phebus scaling-down factor : ~5000

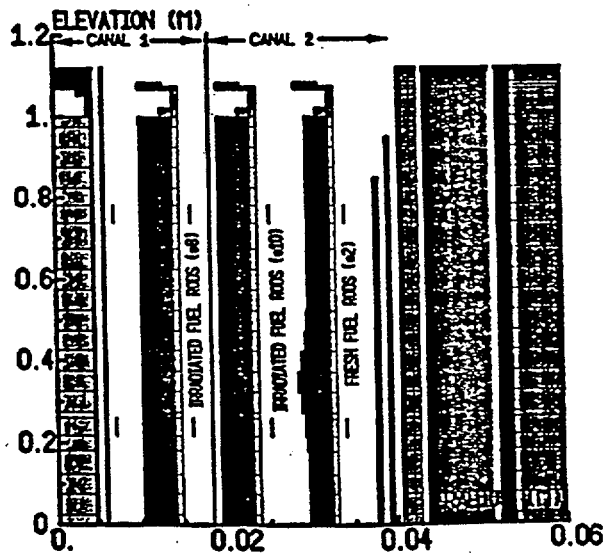


Fuel bundle degradation

PHEBUS FPT1: Boundary conditions and ICARE2 modeling (similar for FPT0)



- 3 Main Phases (Calibration, Oxidation and High Temperature Phases)

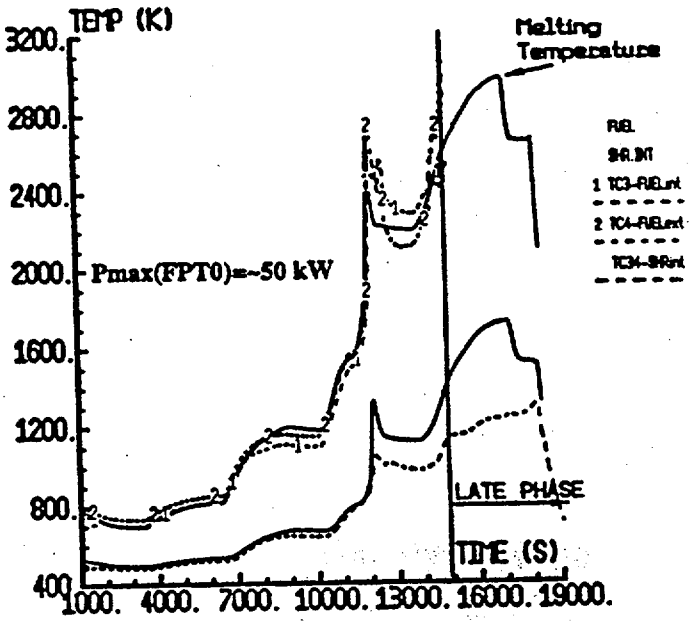


ICARE2 (V2 mod2) modeling

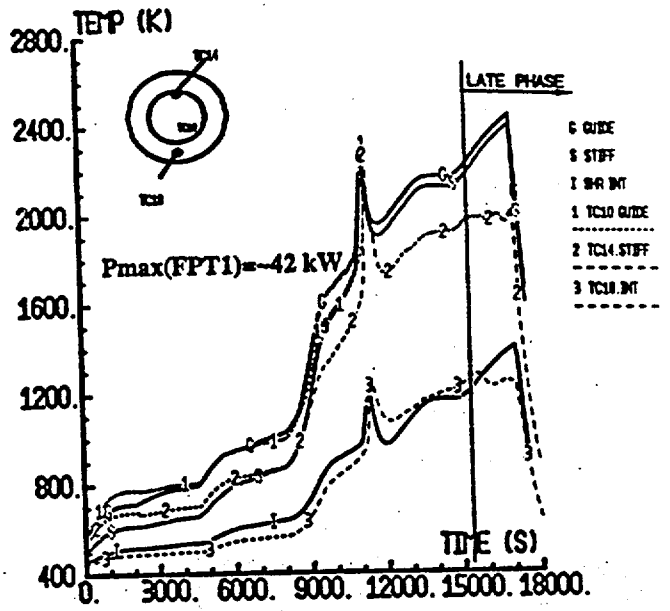
- Main Damage Events Identified during the Test
  - Cladding Burst
  - Control Rod Failure and Relocation
  - Temperature Escalation due to Zry Oxidation
  - Progressive Fuel Relocation observed during

- Detailed Modeling of the different Components
- 2 Radial Fluid Channels, 3 representative Fuel Rods (Irradiated and Fresh Fuel), Grids, UST and Stiffeners
- 22 Axial Meshes for Fuel (from 0 to 1. m elevation)

Temperature histories in the ICARE2 FPT0 and FPT1 calculations



PHEBUS FPT0 : TEMPERATURES AT 0.70 m ELEVATION
TC FUEL, TC INSIDE ZIRCONIA

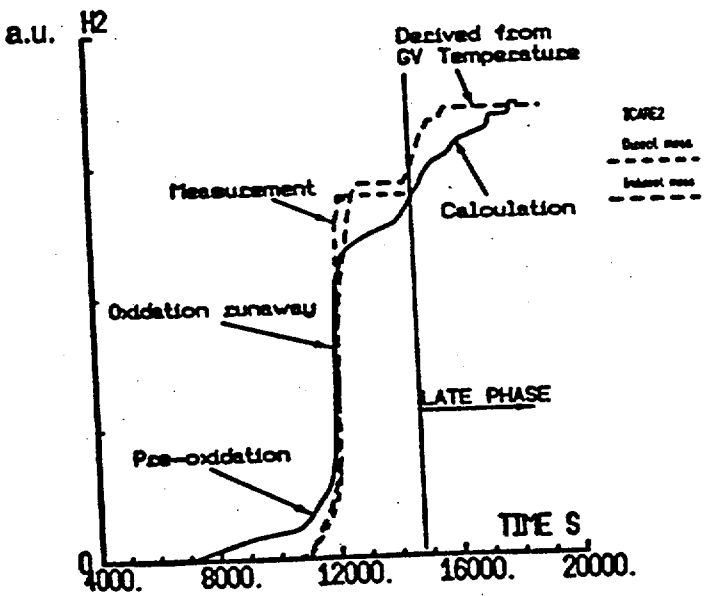


PHEBUS FPT1 : TEMPERATURES AT 0.80 m ELEVATION
GTUBE, STIFFENER, TC INSIDE ZIRCONIA

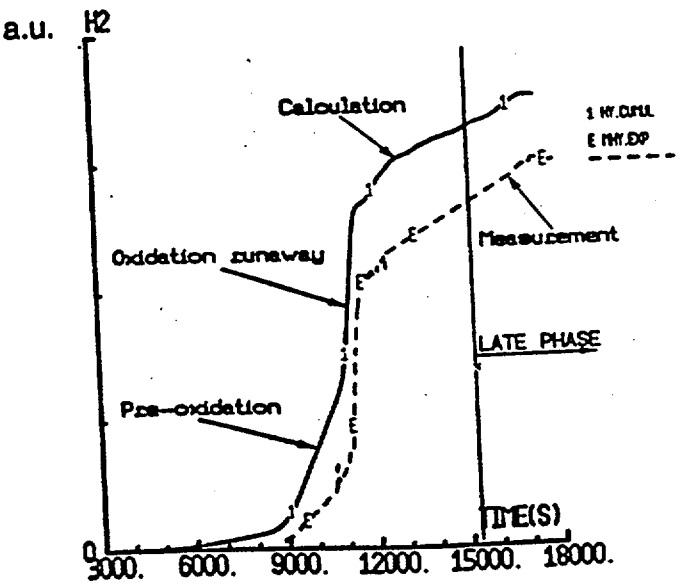
- ► During Oxidation Runaway : larger temperature peak in FPT0 (~2800 K) than in FPT1 (~2400 K)
- ► Code-to-data Discrepencies for the Late Phase due to Progressive Melt Relocation identified at 2540 K in FPT0 and 2450 K in FPT1 (estimation based on the results of the ICARE2 calculations)

Fuel bundle degradation

Hydrogen production in the ICARE2 FPT0 and FPT1 calculations



PHEBUS FPT0 : HYDROGEN MASS PRODUCTION



PHEBUS FPT1 : HYDROGEN MASS PRODUCTION

- ► Calculated H2 Production (Urbanic-Heidrick correlations)
  - ~18% during the Pre-Oxidation Phase (slight overprediction)
  - ~49% during Temperature Escalation

- ► Calculated H2 Production (Urbanic-Heidrick correlations)
  - ~37% during the Pre-Oxidation Phase (slight overprediction)
  - ~38% during Temperature Escalation

Fuel bundle degradation

Conclusions of the FPT0 and FPT1 analyses using ICARE2 code

► Calibration Phase

- Correct prediction of the bundle temperatures. Cladding burst calculated at 1090-1100 K (EDGAR model)

► Oxidation Phase

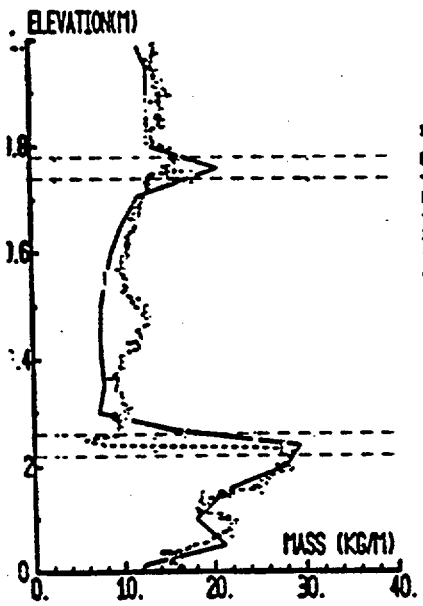
- Correct prediction of the control rod failure using temperature criterion (1730 K=melting temperature of S. Steel)
- Temperature escalation correctly calculated using URBANIC-HEIDRICK correlations assuming intact cladding (criterion for clad dislocation : T>2700 K or T>2600 K and E_{ZrO_2}<250 µm)
- Calculated total H2 production inside the experimental uncertainty range
- Calculated state of the bundle at the end of the oxidation phase : low fuel dissolution by molten Zry (200-400 g in the upper part) due to high cladding oxidation and low bundle degradation

► Melt Progression Phase :

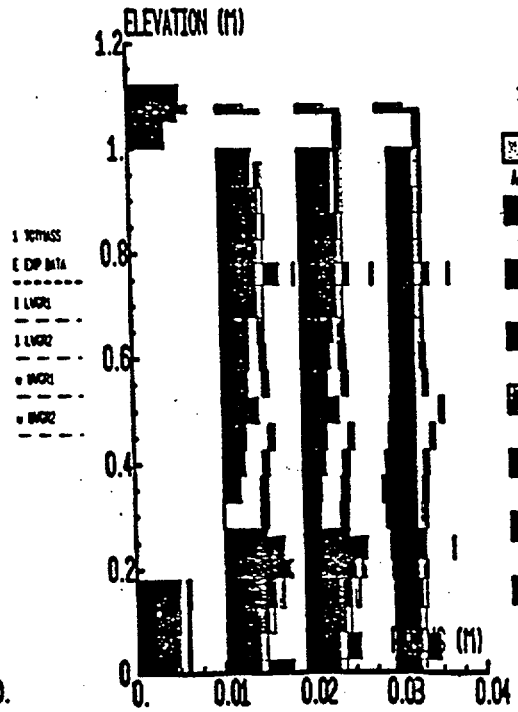
- Large underprediction of the bundle degradation at the end of the calculations
- Correct reproduction of the experimental data using a reduction of the melting temperature of fuel (solidus ~2500 K)
  - ✓ Correct calculation of the temperature responses in the lower part of the shroud
  - ✓ Calculated bundle degradation in better agreement with the post irradiation examinations (estimation of the mass of materials in the frozen molten pool: FPT0~3.2 kg and in FPT1~2 kg)

Fuel bundle degradation

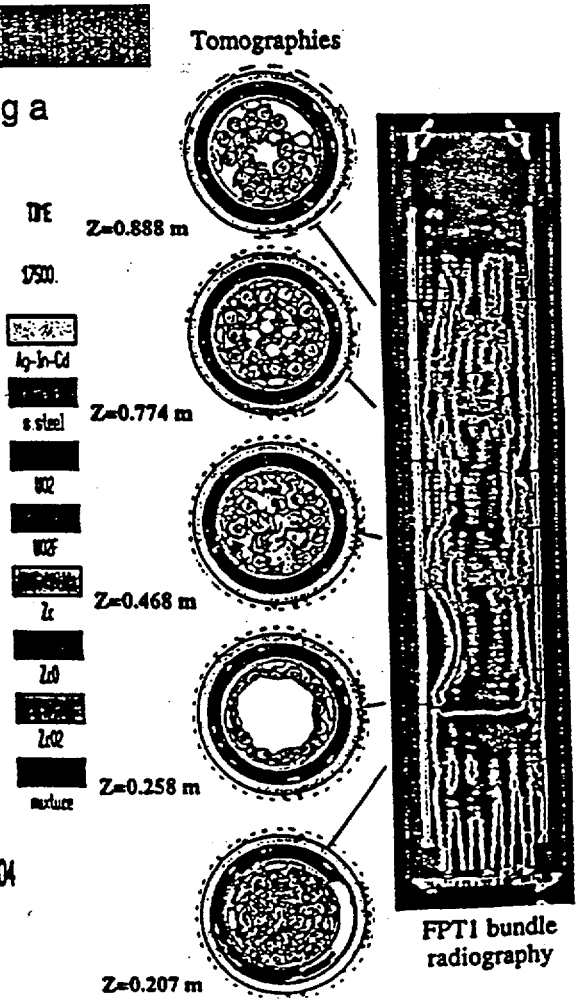
Results of the FPT1 ICARE2 calculation assuming a reduced melting temperature (solidus 2450 K)



Material Distribution (imposed in the calculation in the lower part of the bundle)



PHEBUS FPT1 STATE OF THE BUNDLE AT ~17500 SECONDS



FPT1 bundle radiography

FP release and transport

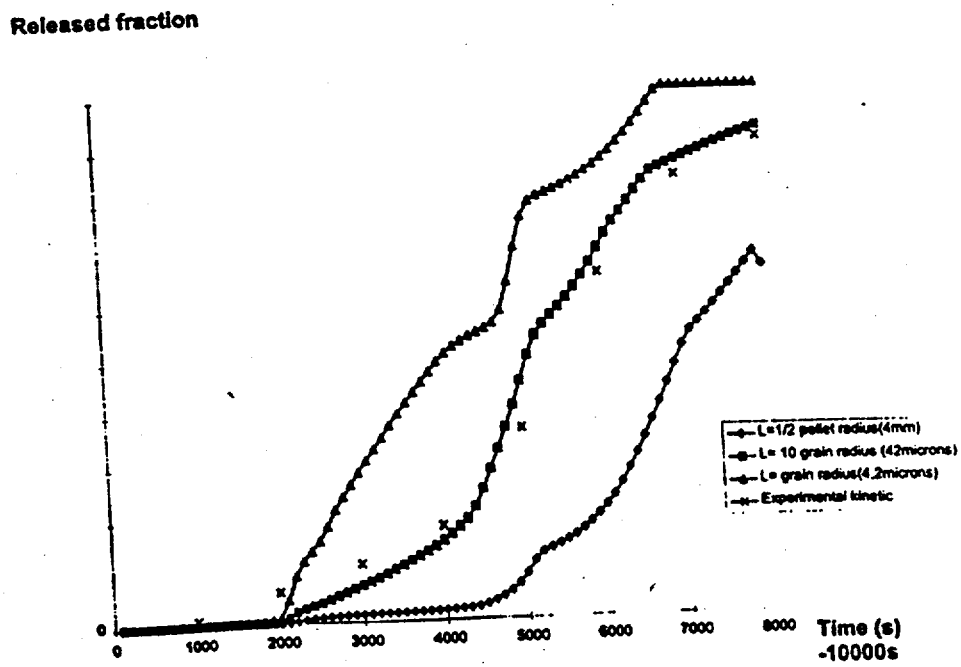
Outline of codes

- FP release:
  - ELSA version 1.1 rév.1: semi-empirical models targeting dominant phenomena,
    - intact fuel,
    - 3 FP categories: volatiles (in-grain diffusion), semi-volatiles (evaporation into porosities), and non-volatile (fuel volatilization).
  - MFPR version 1.0 rév.1: mechanistic (FASTGRASS/VICTORIA type) models,
    - intact fuel,
    - only volatile FPs,
    - initial state from irradiation, grain growth, atomic and bubble (intra & intergranular) migration,
    - Cs and I chemistry, fuel oxidation by steam,
    - volatile FP release following liquefaction.
- FP transport:
  - SOPHAEROS V1.1 (coupled with CATHARE2 V1.3) and V1.3 rév.1:mechanistic vapour and aerosol modelling,
    - vapour-phase chemistry, chemisorption,
    - vapour condensation,
    - aerosol deposition and agglomeration.

FP RELEASE

▷ *ELSA analyses of FPT0*

Iodine release: effect of diffusion distance, L (S/V=50)



SOPHAEROS analysis of FPT1: vapour species

source: I, Cs, Te, Ba, La, Ru, Mo, Ag (72g.), In (13g.), Cd (18g.), UO2 (180g.).

	Cs	I	Te
upper plenum	CsOH, Cs2MoO4 (10^{-7} g/cm^3) ; some CsI ; trace Cs, CsO	AgI, CsI (10^{-8} g/cm^3) ; some I, HI, AgTe ; trace InI, CdI, HIO, CdI2	Te2 (10^{-7} g/cm^3) ; some Te, TeO, I2Te, AgTe ; trace Ag2Te, Te2
point C	Cs2MoO4 (10^{-10} g/cm^3) ; trace CsI, CsOH	I2Te (10^{-8} g/cm^3) ; some HI, AgI, CsI; trace CdI, AgTe	Te2, I2Te (10^{-7} g/cm^3) ; trace Te, H2Te, AgTe, TeO, CdTe
point G	Cs2Te (10^{-12} g/cm^3) ; trace Cs2MoO4	I2Te (10^{-7} g/cm^3) ; trace H2Te	Te2 (10^{-7} g/cm^3) ; some I2Te ; trace Cs2Te, H2Te

SOPHAEROS analysis of FPT0: SG deposition

temperatures: 700 -> 150°C,

unexpected phenomenon: mechanical resuspension during FPT0 inerting (Re=1900, laminar !)

SOPHAEROS results:

- over-estimation of the calculated retention / experimental result:
  - factor 1.4 for iodine (vapour at 700°C),
  - factor 2.5 for caesium and for aerosols.
- ☛ *similar work on FPT1 still in progress.*
- sensitivity studies for FPT0:aerosol thermal conductivity, aerosol size,
  - no improvement in agreement,
  - mechanical resuspension throughout test ?

FP release and transport

Conclusions

volatile FP release:

- ELSA interpretation: suitable diffusion length must be used for low burn-up fuel
- MFPR interpretation (consistent with ELSA): shows slower increase of intragranular bubbles, and thus a later opening of porosities in FPT0 compared to FPT1.

  ☛ *correct phenomenological sequence, but wrong timing.*

semi-volatile FP release:

- ELSA evaluation: too high for FPT0 and FPT1, but model validated on analytical tests.

  ☛ *paradox unexplained at present.*

FP transport:

- SOPHAEROS can explain broadly the experimental results, producing a consistent image with candidate FP species,
- gas-phase chemistry is crucial.

  ☛ *impact of transitional metals (and silicon) on Cs and I behaviour is marked.*

FP behavior in the containment

FPT0 Thermalhydraulics behavior

the behavior of the containment vessel (REPF 502) is controlled by the imposed wall temperatures and by the steam and H2 mass flow rates.

satisfactory simulation with the 0D JERICHO code (part of ESCADRE), particularly the condensation flow rate:

- when using the Reynolds analogy (negligible heat and mass transfer coupling) and the Chilton-Colburn or Collier models,
- but under-prediction of the steam pressure with the Uchida correlation.

complementary calculations with the mechanistic 3D code TRIO.VF (CEA)

- confirms the JERICHO hypothesis of a well-mixed atmosphere,
- shows a mixed convection flow pattern:
  - natural convection in the lower part of the vessel, and far from condensers,
  - jet influence in the upper part of the vessel, and face to the condensers.

☛ *current applications of the multi-compartment code RALOC (part of the ASTEC code) on FPT0 and FPT1.*

FPT0 and FPT1: Iodine behaviour

Main results : FPT-1 test confirmed the overall behaviour observed in FPT-0:

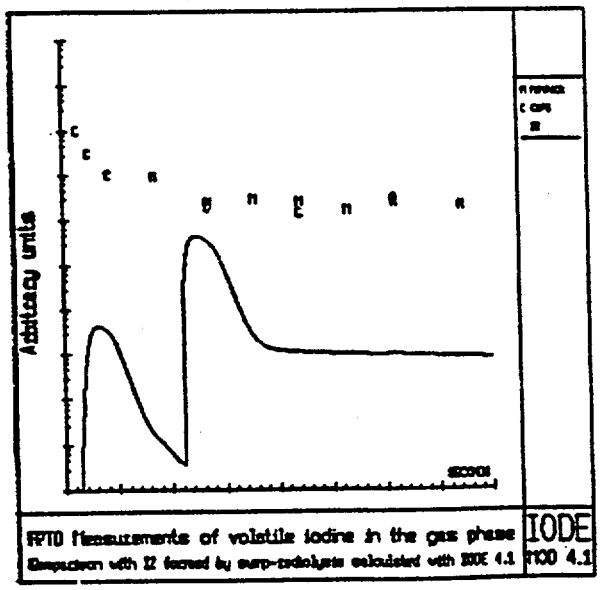
- presence of gaseous iodine in the containment during early degradation phase explained by iodine injected in gaseous form from the circuit.
- iodine rapidly deposited in the sump as insoluble AgI; consequently, no observed revolatilisation of iodine due to radiolysis, even though the sump pH was acid.
- gaseous iodine on the long term produced by release from containment surfaces (potential mechanism : organic iodides production from painted condenser surfaces); obtention of equilibrium concentrations.

Implications for modelling of iodine chemistry in the containment:

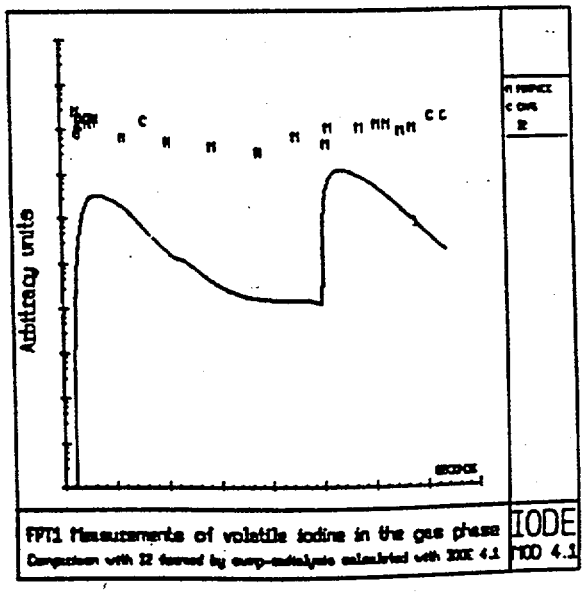
- inadequate current modelling in IODE mod 4.1 (iodine concentrations and partition determined from formation of volatile iodine in the sump, transfer to the containment atmosphere, loss by deposition on surfaces).
- necessary developments (besides developing a better understanding of RCS chemistry) will be integrated in future versions of the code IODE :
  - modelling of kinetics of organic iodides formation/decomposition,
  - modelling of Ag/I interactions describing Ag chemistry in the containment (oxidation processes), AgI formation and stability.

FP behavior in the containment

FPT0 and FPT1: Iodine behaviour



FPT0 Measurements of volatile iodine in the gas phase
Comparison with I2 formed by sump-radiolysis calculated with IODE 4.1



FPT1 Measurements of volatile iodine in the gas phase
Comparison with I2 formed by sump-radiolysis calculated with IODE 4.1

Conclusion

- the whole analysis of the first two PHEBUS.FP tests (FPT0, FPT1) already led to improvements of models in some of the codes or to reorientation of R&D programs on open problems, for instance:
  - fuel liquefaction temperature,
  - importance of thermochemistry in primary circuit: existence of gaseous Iodine at the entrance of the containment, low volatility of Caesium at 700°C,
  - trapping of Iodine by Silver in the sump water.

- the updated codes (ICARE2, ELSA, SOPHAEROS, RALOC,...) are now in use preparing the next PHEBUS.FP experiments (FPT2 and FPT4).

Current Status of VEGA Project and Analytical Activities on Aerosol Behavior at JAERI

A. Hidaka, T. Nakamura, Y. Harada, T. Kudo and J. Sugimoto
Japan Atomic Energy Research Institute

Presented at Spring 1998 CSARP Meeting
May 4-7, 1998, Bethesda, U.S.A.

Current Status of VEGA Project and Analytical Activities on Aerosol Behavior at JAERI

Akihide HIDAKA, Takehiko NAKAMURA, Yuhei HARADA, Tamotsu KUDO and Jun SUGIMOTO
Japan Atomic Energy Research Institute

Abstract

VEGA (Verification Experiments of Gas/Aerosol release) project has been performed at JAERI to investigate the release of FP (Fission Products) including non-volatile or short-life radionuclides from Japanese LWR fuel at ~3000℃ under high pressure condition up to 1.0 MPa. Fundamental capabilities of experimental facility have been confirmed. The facility is being installed into hot cell and will be completed in June, 1998. Two preliminary experiments during FY1998 and four experiments in a year after FY1999 are scheduled. Pre-test analysis for preparation of operational conditions will be conducted with VICTORIA code. Fabrication of ThO_2 tube was mostly successful by using centrifugal slip casting technique and will be continuously examined for the use in VEGA experiments after FY1999. FP release from MOX of ATR Fugen will be investigated in future.

It was recently pointed out that the integrity of steam generator (SG) tube during secondary system depressurization would be threatened by a large pressure difference between primary and secondary systems and temperature increase by hot leg counter current flow and decay heat from deposited FPs. In order to investigate the effect of decay heat from deposited FP on the steam generator tube integrity, FP behavior in SG during a total station blackout (TMLB') sequence of Surry nuclear plant with and without secondary system depressurization was analyzed at first with JAERI's ART code. The analysis showed that relatively large amount of FPs may deposit on SG U-tube inlet surface mainly by thermophoresis. As a next step, the thermohydraulic and structural response analysis with SCDAP/RELAP5 was performed and predicted a small safety margin for SG U-tube integrity during secondary system depressurization. Taking into account uncertainties in the present analysis, the potential for steam generator tube rupture (SGTR) after core heat up cannot be ignored during secondary system depressurization.

Contents

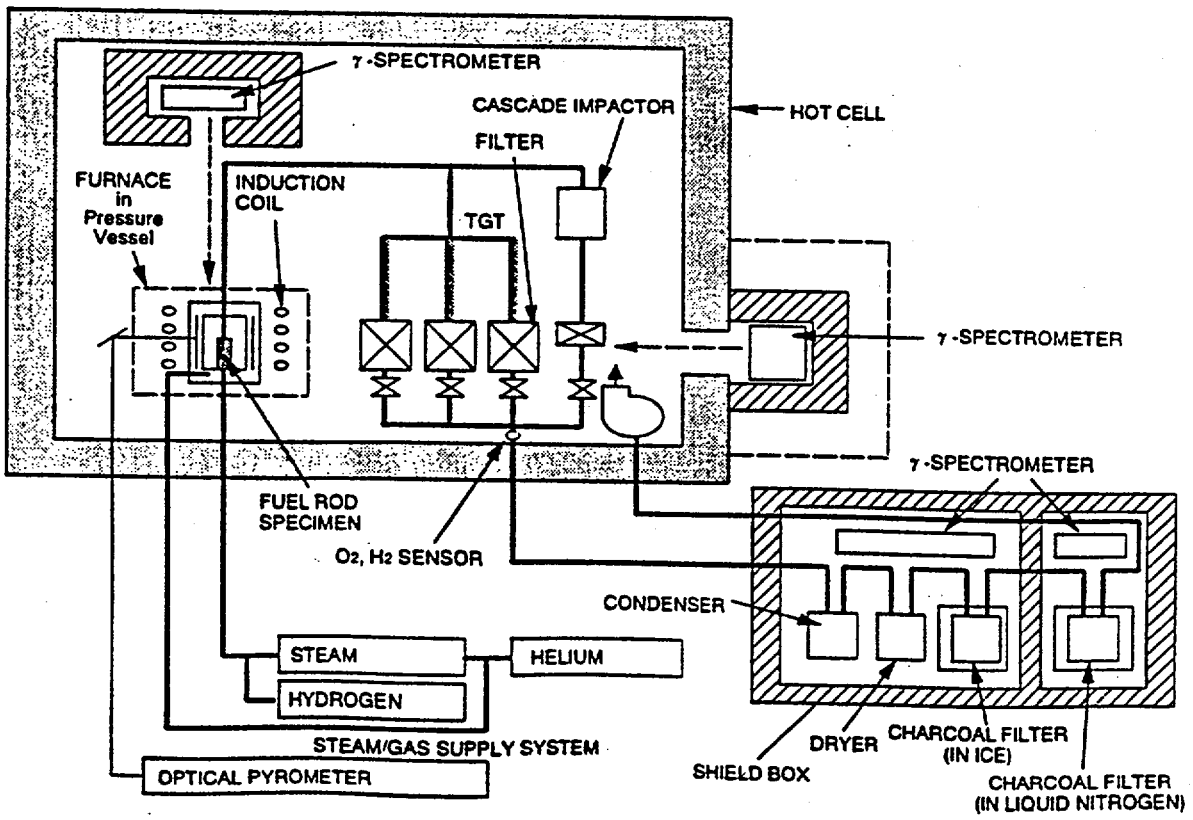
1. Introduction

- Large uncertainties in FP gas/aerosol release and transport under severe accident conditions
- VEGA (Verification Experiments of Gas/Aerosol Release) project at JAERI to investigate FP release from LWR fuel at ~3000℃ under high pressure (1.0MPa) condition
- Analysis of FP behavior in SG tube in case of secondary system depressurization to investigate the tube integrity during severe accidents

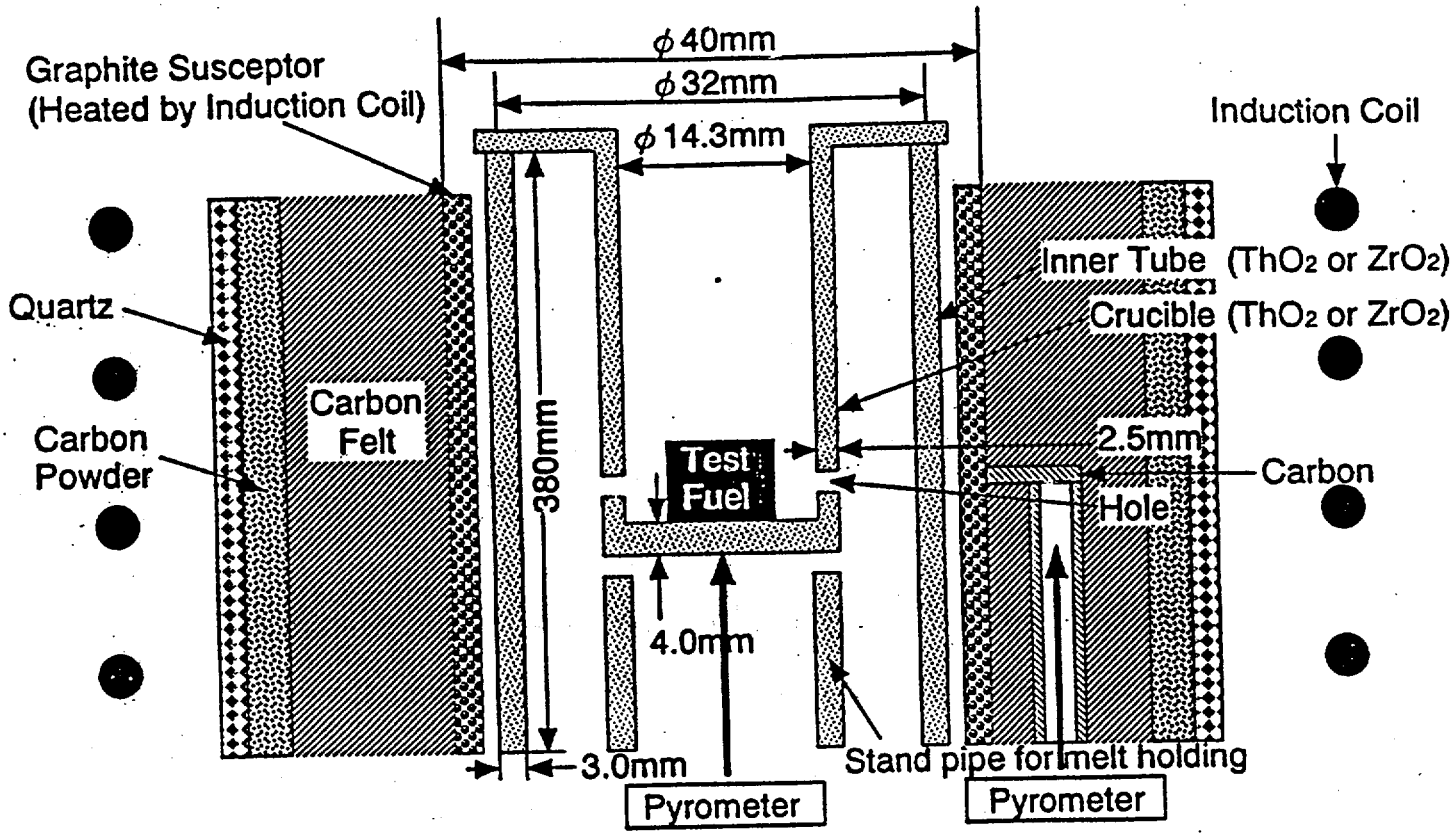
2. Status of VEGA Project

- Objectives
  - To obtain FP release data from fuel under severe accident conditions
  - To investigate FP behavior in reactor core and coolant system
- Special Targets
  - FP release from high temperature fuel (including debris bed)
  - Effect of ambient pressure on FP release
  - Non-volatile/short-life FP release

VEGA Facility

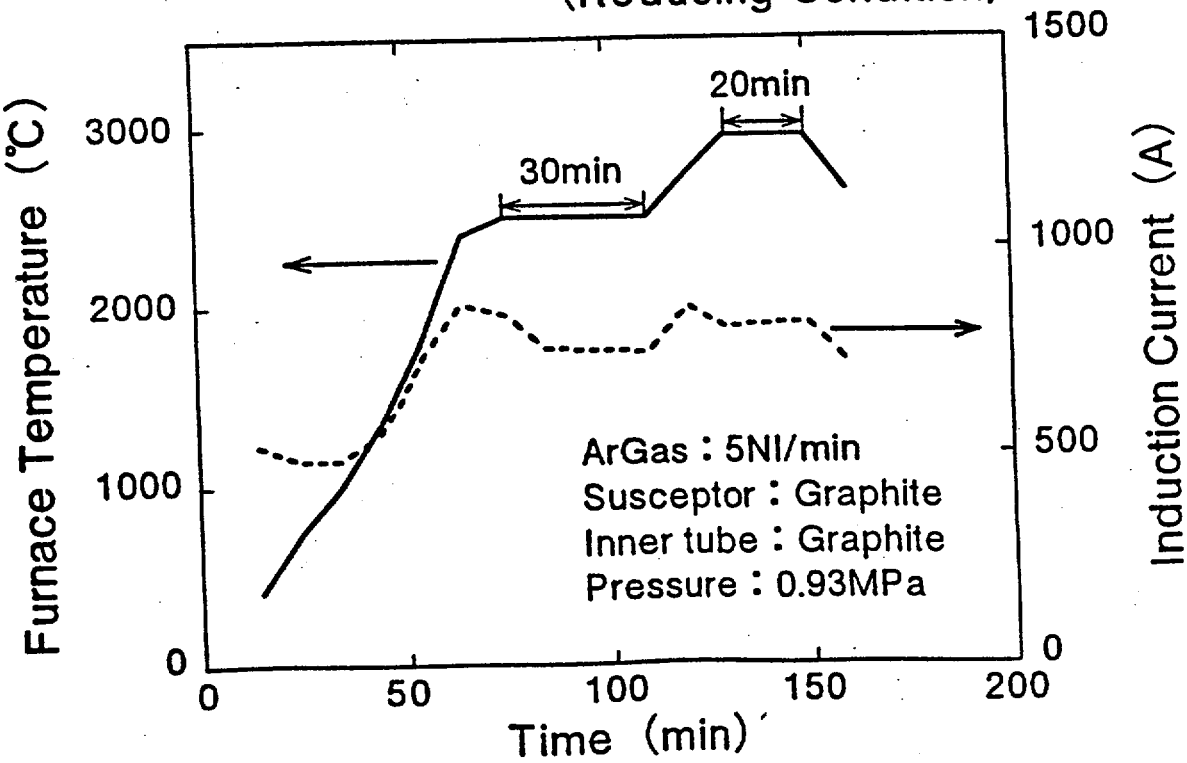


Schematic of VEGA Furnace



Heat-up Test with VEGA Furnace

(Reducing Condition)



Experimental Conditions

- Test sample ; 6cm long, 100g
  - BWR Tsuruga Unit 1 ; 26GWd/tU
  - PWR Mihama Unit 2 ; 39GWd/tU
    Ohi Unit 1, 2 ; ~50GWd/tU
  - TMI-2 debris sample
  - ATR Fugen ; MOX fuel
- Re-irradiation of test fuel using NSRR to accumulate short-life radionuclides
- Max. temperature ; 3000℃
  (Isothermal induction heating in ZrO_2 or ThO_2 tube furnace)

Measurement

- On-line gamma measurement
  - Filters or Impactor : Cs-137, I-131, Ba-140 (La-140)
  - Charcoal traps : I-131
  - Cooled charcoal : Kr-85, Xe-133
- 3 Thermal Gradient Tubes (750-200℃)
- On-line oxygen/hydrogen measurement
- Off-line gamma spectrometry
- SEM/EPMA, SIMA
- Metallography
- ICP-MS (for solution)

Fabrication of ThO_2 Tube

■ Requirement for Furnace Material

– Stable under high temperature > 3000℃ and oxidized conditions

	M.P. > 3000℃	Stability under oxidized condition	Remark
ThO_2	○ (3370℃)	○	Nuclear material
W	○ (3382℃)	×	Expensive
ZrO_2	× (2677℃)	○	Use in Exp. (< 2400℃)

■ Method for Fabrication ; Centrifugal slip casting technique

– Slip preparation by changing water, water dispersant and binder

Slip No.	1	2	3	4	5	6
ThO_2 powder (g)	1400	1400	1400	1400	1400	1400
Water (%)	35	30	32.5	35	35	35
Water dispersant (%)	0.3	0.3	0.3	0.35	0.3	0.3
Binder (%)	0.54	0.54	0.54	0.54	0.34	0.73
Viscosity (mPa•s)	60	2939	507	69	50	542
Sintering at 1700℃	○	× (Crack)	×	×	×	×

Preliminary VEGA Test Schedule

FY		1998	1999	2000	2001	2002	2003	2004	2005
Target		Preliminary test	Test initiation	3000℃ high pressure	He carrier gas	Effect of burn up	ATRMOX test start	ATRMOX 3000℃	Synthetic tests
Experimental Condition	1	2400℃ 0.1MPa H_2O/P	2800℃ 0.1MPa H_2O/P	2800℃ 0.1MPa H_2O/B	3000℃ 0.1MPa H_2O/B(NS)	3000℃ 1.0MPa H_2O/B(NS)	2400℃ 0.1MPa H_2O/MOX	3000℃ 0.1MPa H_2O/MOX	not decided
	2	2400℃ 1.0MPa H_2O/P	2400℃ 0.1MPa H_2O/B	3000℃ 1.0MPa H_2O/P(NS)	3000℃ 0.1MPa He/P	3000℃ 0.1MPa H_2O/P Low burn up	2400℃ 1.0MPa H_2O/MOX	3000℃ 1.0MPa H_2O/MOX	not decided
	3		3000℃ 0.1MPa H_2O/P(NS)	500/1200℃ 0.1MPa Air/P	3000℃ 1.0MPa He/P	3000℃ 0.1MPa H_2O/P High burn up	2800℃ 0.1MPa He/MOX	500/1200℃ 0.1MPa Air/MOX	not decided
	4		3000℃ 0.1MPa He/TMI	3000℃ 1.0MPa He/TMI	500/1200℃ 1.0MPa Air/P	Make-up Exp.	2800℃ 1.0MPa He/MOX	500/1200℃ 0.1MPa Air/MOX	not decided

Note) P : PWR fuel B : BWR fuel NS : NSRR irradiation TMI : TMI debris

3. Analysis of FP Behavior in SG Tube during Secondary System Depressurization

3.1 Introduction

- Resolution of DCH issues for PWRs
  - Failure of hot-leg or surge line prior to RPV meltthrough
- Secondary system depressurization as one of AM procedures for high pressure sequence
  - Primary system depressurization followed by HPI activation or ACC injection
- Questionable SG U-tube integrity during secondary system depressurization
  - Pressure difference and temperature increase by CCNC and FP decay heat

- Hot-leg or surge line failure prior to SGTR is preferable from a view point of AM.
- Recent SCDAP/RELAP5 analyses by USNRC showed SG U-tube integrity during secondary system depressurization.
  - No FP decay heat in the analysis
- Objectives of present study
  - To evaluate FP deposition and decay heat at SG tube with JAERI's ART
  - To investigate effect of decay heat on SG tube integrity during secondary system depressurization with SCDAP/RELAP5

3.2 Analytical Method

- Reference plant
  - Surry plant (Westinghouse 3-loop PWR, 2441MWt)
- Analytical sequence
  - TMLB' (with/without secondary system depressurization)
  - All MSRVs opening at 300s after accident initiation

(1) FP deposition Analysis

- Computer code
  - ART/Mod2 developed by JAERI
- Boundary conditions for ART calculation
  - CsI/CsOH concentrations in superheated steam based on similar MELCOR calculation

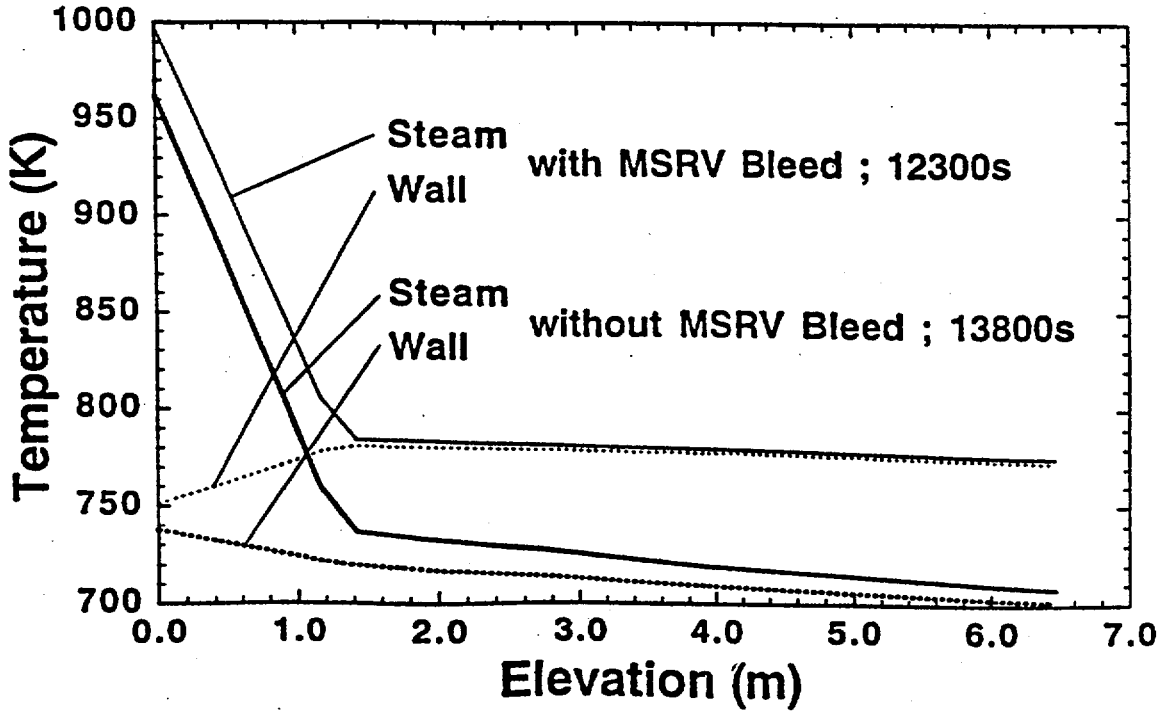
* CsI gas concentration = 0.006kg/m^3
* CsOH gas concentration = 0.040kg/m^3

  - Gas/wall temperatures at SG U-tube equal to SCDAP/RELAP5 calculation without decay heat
- Decay heat calculated by ART was given to surge line, hot leg and SG U-tube heat structures in SCDAP/RELAP5 calculation.
- Assumptions
  - FP deposition occurs when fuel temperature reaches 1500K.
  - Constant decay heat used in the calculation was decided based on FP deposition calculation for 2000s

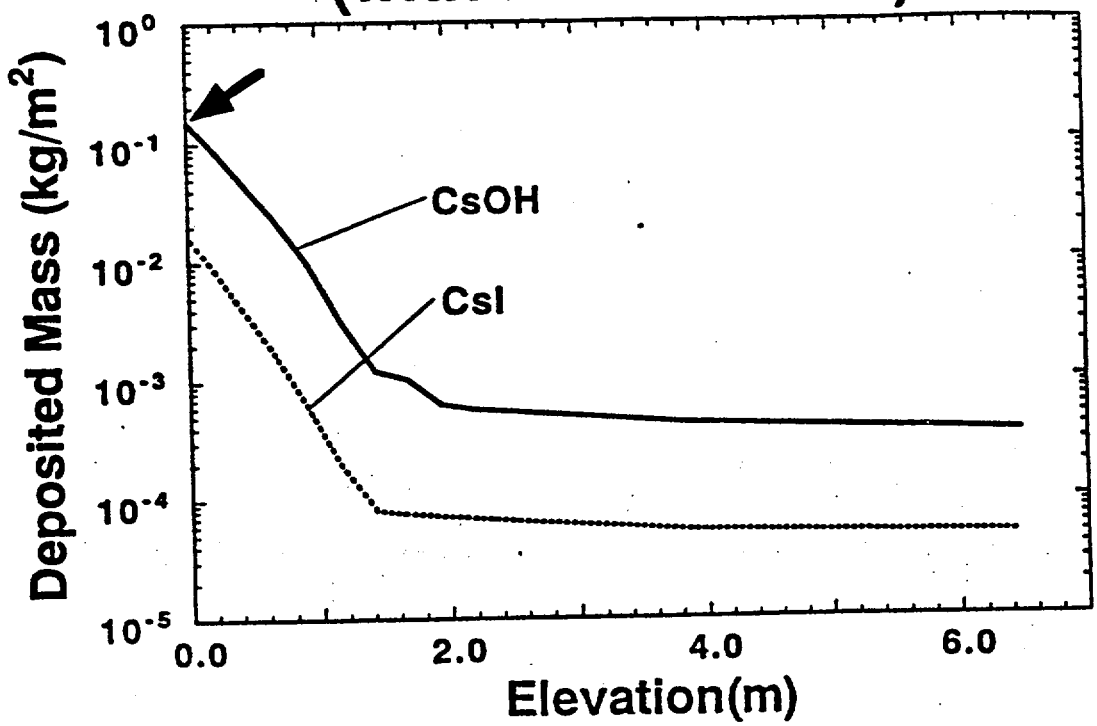
(2) Thermohydraulic and Structural Response Analysis

- Computer code
  - SCDAP/RELAP5/Mod3.1 (Release D)
- Input data prepared originally by INEL
  - Use of hot-leg CCNC model after the onset of core heat up
  - CCNC model prepared based on Westinghouse 1/7 scale model experiment
- Creep rupture calculation for hot leg, surge line, SG U-tube and RPV bottom head by Larson-Miller theory
- Break area = $0.19034 ft^2 = 0.01769 m^2$

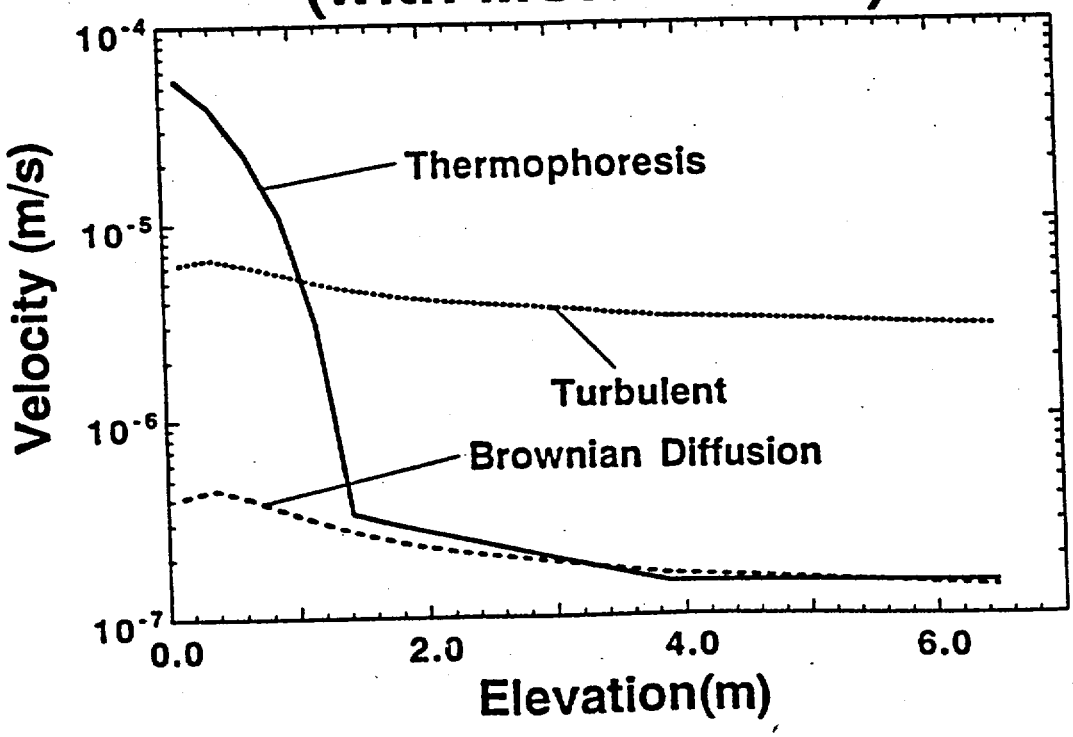
3.3 Analytical Results
Temperature Distribution in SG U-Tube



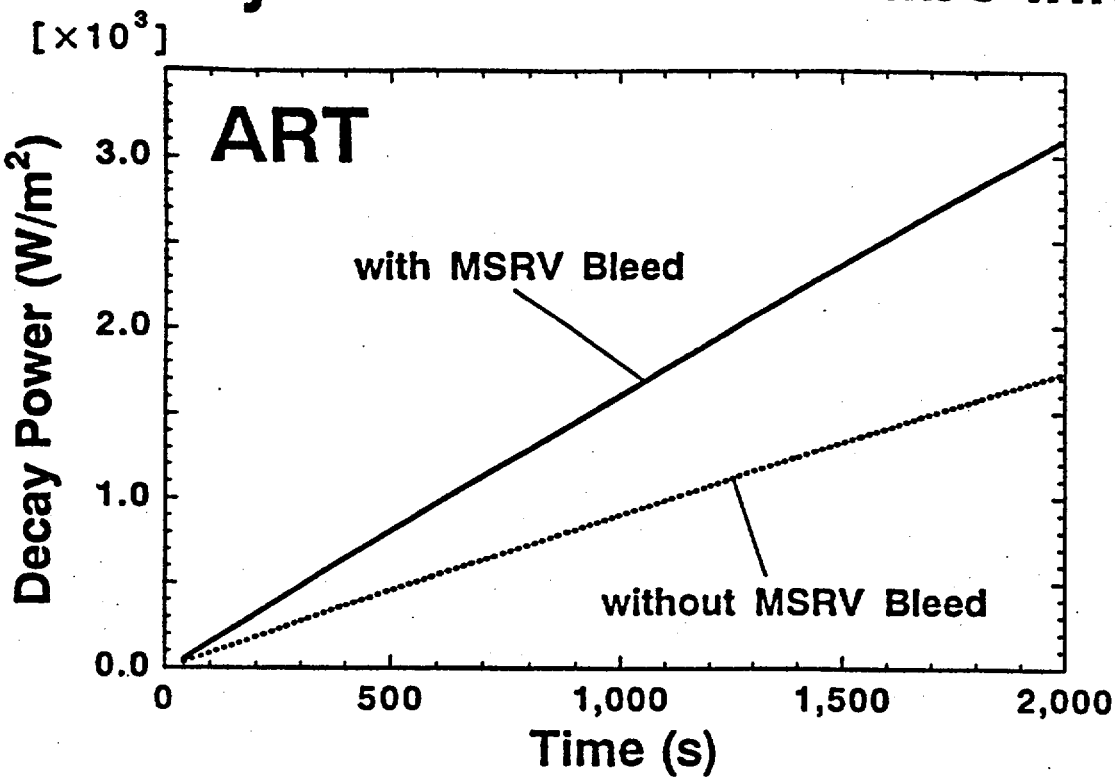
Deposited Mass at SG U-Tube (with MSRV Bleed)



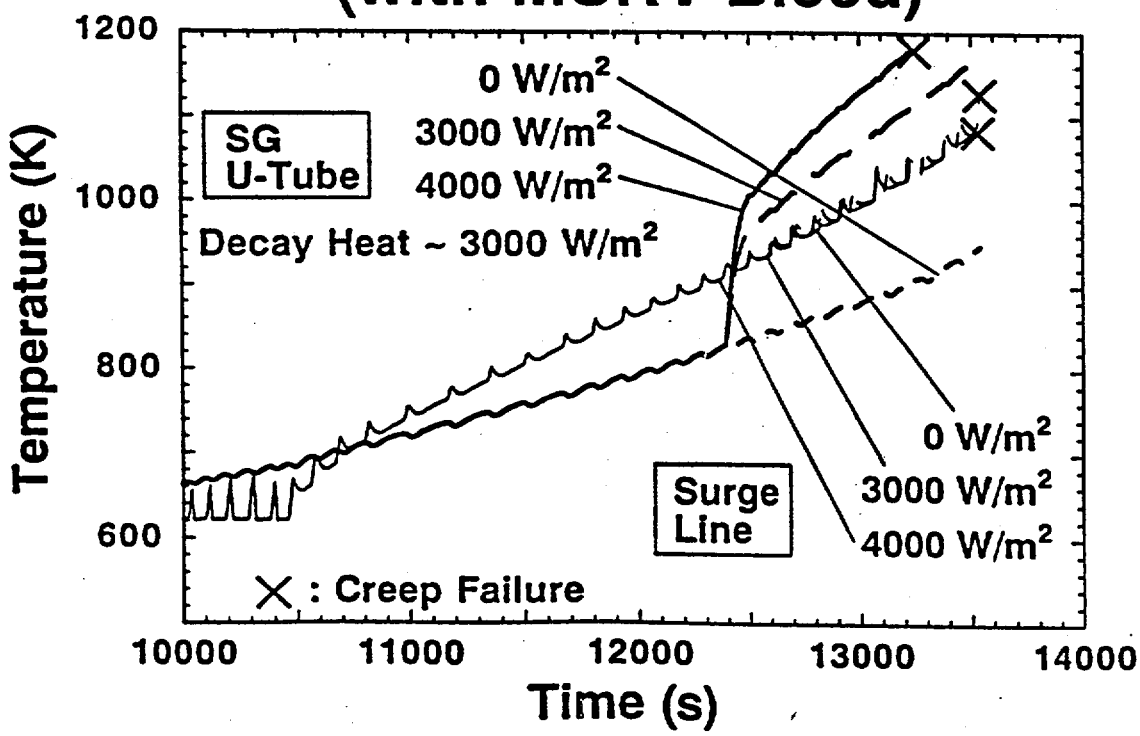
Averaged FP Deposition Velocity (with MSRV Bleed)



Decay Power at SG U-Tube Inlet



U-Tube and Surge Line Temperatures (with MSRV Bleed)



4. Summary (1/2)

(1) VEGA Project

- Fundamental capabilities of experimental facility have been confirmed.
- The facility is being installed into hot cell and will be completed in June, 1998.
- Two preliminary experiments during FY1998 and four experiments in a year after FY1999.
- Pre-test analyses will be conducted with VICTORIA code.
- Fabrication of ThO_2 tube will be continuously examined.
- FP release from MOX of ATR Fugen will be investigated in future.

4. Summary (2/2)

(2) FP Behavior Analysis in SG U-Tube

- FP behavior in SG U-tube during TMLB' with and without secondary system depressurization was analyzed with ART.
- Present analysis showed that relatively large amount of FPs may deposit on SG U-tube inlet surface mainly by thermophoresis.
- Thermohydraulic and structural response analysis with SCDAP/RELAP5 predicted small safety margin for SG U-tube integrity during secondary system depressurization.
- Considering associated uncertainties, potential for SGTR after core heat up cannot be ignored during secondary system depressurization.

ASTEC integral code
Status of development and validation
First application to PHEBUS.FP

F.Jacq, W.Plumecocq, J.P.Van Dorsselaere*
C.Bassi**
H.J.Allelein, W.Klein-Hessling, J.Bestele***

* IPSN/DRS/SEMAR Cadarache, France
** IPSN/DPEA/SEAC Fontenay-aux-Roses, France
*** GRS Köln and Garching, Germany

Contents

- ASTEC context and objectives
- Status of ASTEC V0 version
- First ASTEC applications to PHEBUS.FP (FPT0, FPT1)
- Perspectives for the ASTEC V1 version

Abstract

The ASTEC integral code is developed in close collaboration by IPSN and GRS for the evaluation of source terms during LWR severe accidents. After the 1997 CSARP paper presenting the ASTEC project, this paper focuses on the main progress on validation and applications.

The version V0.1 was internally delivered beginning of 1998 to IPSN and GRS users, with a first set of test-cases and with a user's documentation in-line. A «consolidation» phase is currently performed with a comparison with the IPSN reference code, ESCADRE, on 15 reactor-cases.

The validation of the version V0 is currently performed on «separate-effect» experiments on French, German and foreign programs (TUBA, VERCORS, DCH-ANL, BETA, VANAM, HDR, KAEVER,...). A first stage of validation is foreseen mid-98 on about 25 tests which cover the main phenomena and could allow first reactor applications for the French PSA2 studies. Some first results of the validation are presented here.

An important action is the validation on the integral PHEBUS.PF experiments, i.e. the FPT0 and FPT1 ones.

The FPT0 application is up to now focused on the bundle degradation phase with the VULCAIN module. With a space modelization similar to ICARE2 and MAAP4 ones, a global agreement is obtained on the sequence of events, particularly on fuel clad rupture (using the Chapmann correlation) and on Zry oxidation (hydrogen produced mass and kinetics). But discrepancies remain on the chronology (delays on control rod rupture and on fuel collapse).

The FPT1 application is run up to now with parallel uncoupled applications to the primary circuit on one hand (some preliminary results are presented here), and to the containment on the other hand :

- as for the circuit, the coupling of the following modules, VULCAIN (bundle degradation)-ELSA (FP release)-SOPHAEROS (FP and aerosol transport), gives satisfactory results. The global agreement with the experimental results is good, and the calculations of the bundle degradation are consistent between FPT0 and FPT1.
- in the CPA module for the containment, thermalhydraulics (based on RALOC), aerosol behaviour (based on FIPLOC) and iodine behaviour (based on IODE) are coupled.

The complete coupling of all the modules will be performed in the next months.

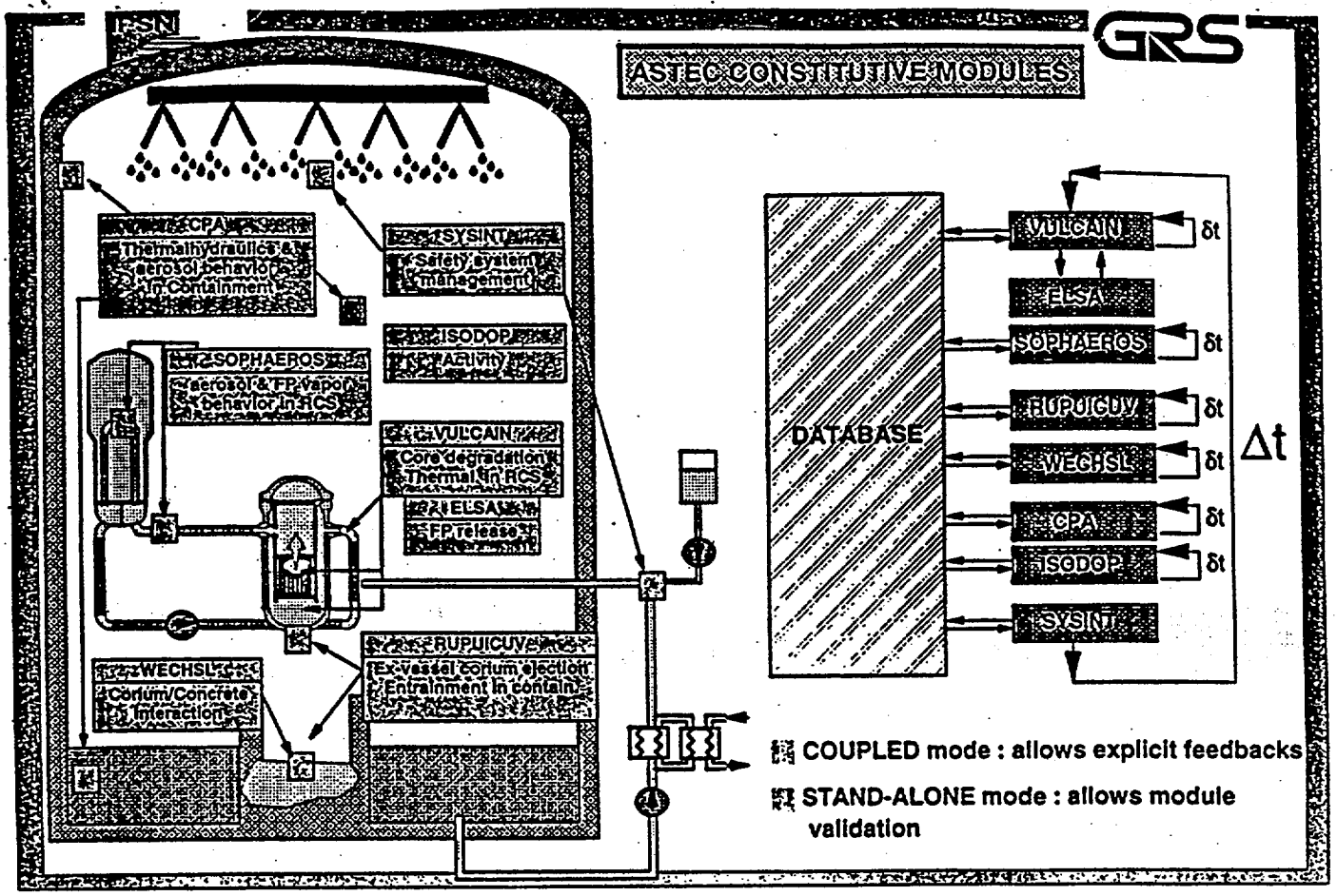
Finally, the perspectives for the next version V1 (scheduled for end 1999-beginning 2000) are summed up:

- RCS 2-phase simplified thermalhydraulics during both the front end and the core degradation phases,
- new core degradation module, based on ICARE2 structure and simplified models,
- possible improvement or replacement of the WECHSL module for the MCCI,
- updating of some constitutive modules (ELSA, SOPHAEROS and IODE).

ASTEC Context and objectives

Summary of the CSARP 1997 presentation

- IPSN/GRS cooperation for an integral code for LWR source term severe accident calculation.
- Main requirements: PSA2, accident management.
- Specifications:
  - the best modeling from IPSN/GRS integral approach,
  - «reasonable» calculation time (fast-running code),
  - accounting for safety systems and their availability.
- Coupling with the IPSN SUNSET tool for statistical analysis.
- Version V0 based on the best models from:
  - ESCADRE mod 1.1 IPSN integral code for the RCS and for Iodine behaviour in the containment,
  - RALOC/FIPLOC (CPA) GRS codes for aerosols and thermalhydraulics in the containment.
- SIGAL data-base: stand-alone running mode or coupled running mode.
- Total IPSN+GRS mannower: about 10 men/year.



Status of ASTEC V0 version

- Internal release of the V0.1 version to IPSN and GRS users in January 1998, with:
  - 13 test-cases on «separate-effect» experiments,
  - 5 reactor test-cases on PWR 1300 MWe (4 tests with one compartment and 1 test with 45 compartments),
  - with user's documentation on-line: performed to 95%.
- Current «consolidation» of the version V0.1:
  - comparison with ESCADRE mod 1.1 on the 15 single-compartment reactor-cases used for ESCADRE delivery,
  - extension to other reactor multi-compartment tests (TMLB, S2CD, A, AB).
  - completion of the documentation.
  - *continuous corrective evolution, with a mid-98 objective of a version able to be used for French PSA2.*
- Validation:
  - minimum validation document for mid-98: 25 separate-effect tests,
  - complementary validation in late 1998 and in 1999 (PHEBUS.FP, TMI-2, ...).
  - current application to the PHEBUS.FP integral tests FPT0 and FPT1.

ASTEC V0 - Basic Validation Matrix

15.4.98

	HDR E11.2 E11.4	HDR E12.3	BMC Gx4	VANAM M3	KAEVER 148 149 151	NUPEC M7.1	PHEBUS /TH/	PITEAS 8.FPA1	ORNL hydrolysis	SREAS multiphase	ACN RTF 3B	PHEBUS RTF3	PHEBUS RTF5	HI-VI 1-6	HEVA 6	VERCORS 4	VERCORS 1-2	CORA 13	PHEBUS B9+	PBFSFD 1.4	LOFT FP2	ACRR MP 2	PHEBUS FPT0 FPT1
CPA-THY-RALOC																							
H_2 Combustion		O,D																					
Pass.Autocat Recomb.			O																				V
Temp. distribution (stratific. or mixing)	O	O,D	O	O,D		O,D	O																V
light gas distribution	O		O	O,D		O,D																	V
steam distribution	O		O	O,D		O,D	O																V
Convection pattern	O		O	O,D		O,D	O																V
Steam cond. on wall	O		O	O,D	O,V	O,D	O	O,V															V
Sensible heat transfer	O	O,D	O	O,D	O,V	O,D	O	O,V															
Spray system	O					O,D		O,V															V
Sump evaporation	O					O,D	O																V
FP decay heating																							
Boiling																							
CPA-AER-FIPLOC																							V
Agglomeration				O,D	O,V																		V
Sedimentation				O,D	O,V																		V
Diffusion deposition				O,D	O,V																		V
Diffusiophoresis				O,D	O,V																		V
Condensation on aerosols				O,D	O,V																		V
Condensation on hygros. aerosols				O,D																			
Multi-comp. effects				O,D																			
Turbulent diffusion																							
Resuspension																							
CPA-IODE									O														V
Thermal reactions in water										O	O,D	V	V										V
radiolytic. Reactions mineral species Sump												V											V
reactions AgI in Sump																							V
Radiolytic reaction atmosphere (ozon)																							
unorganic iodides											O,D	V	V										V
organic iodides											O,D	V	V										V
Sump-atmosph. volatile species mass transfer											O,D	V	V										V
Deposition on solid surfaces													V										V
effect of steam condensation on walls																							
water droplets-atmosphere mass transfer																							V
particulate iodine behav.																							
Multi compartments aspects																							
VULCAN																					V	V	V
Clad ballooning																					V	V	V
oxidation																					V	V	V
eutectic melts																			V	M	V	V	V
fuel dissolution																					V	V	M V
ceramic melts																			V		V	V	M
particulate debris																					V		M V
molten pool																			V			V	
core reflooding																					V		M
crust failure																							V
struct. ablation																					V	V	V
FP rel. and transp.																							
ELSA															O	D	D	O,M					V
Volatile FP															O	D	D	O,M					V
Low volat. FP																							
No volatile FP																							

ASTEC V0 - Basic Validation Matrix

15.4.98

	ACE L2/5/7	BETA 1.8	ANL U2	ANL U1A UB	ANL IET3	ANL IET7	SNL IET4	SNL IET6 IET10	SNL IET8B	SNL IET11	KAERI	TUBA TT28	TUBA TD7	DEVAP 08	AERODEVAP 04	TRANSAT TR2	FALCON 18	PHEBUS FPTO, FPT1
RUPUICU																		
Prot. corium			O,D	O,D							V							
H_2 burning			O,D				O	O		M	V							
Scale effect						O		O			V							
entrainment (driving press.)			O,D	O,D	O	O	O	O			V							
Cavity water mitigation.									M									
Insulat.disrupt.mitig.										M								
SOPHAEROS																		
Aerosols settling																M		V
Laminar diffusion												M						V
Turbulent diffusion																M		V
Eddy impaction.																M		
Bend impaction.																M		V
Thermophoresis.												M						V
Diffusiophoresis													D					V
Vapor FP .cond./evap. on walls														O	M		D	V
Vapor FP cond./evap. on aerosols															M			V
Sorbtion														O	M		D	V
WECHSE/CALTHER'S																		
Zirconium content	O,D	O,D																
R H C up. surface		O,D																
2 layers (oxi/metal)		O,D																
1layer (met. disper. in oxid.)	O,D																	
Siliceous concrete	O,D	O,D																
limest. sand concrete	O,D	O,D																

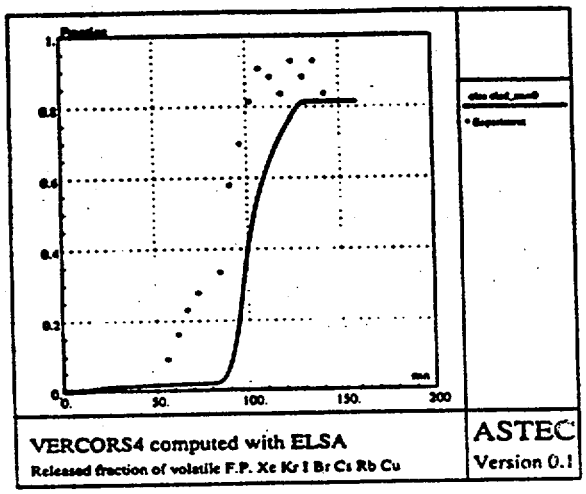
- O : means validation performed with an old (stand alone) version
- D : means valid. calculation performed with ASTEC V0 as ***Delivering Case*** which were performed until the delivering of ASTEC V0;
- M: ***Minimum Validation stage*** to be performed to allow first reactor applications for instance for PSA. Milestone mid 1998
- V : means complementary validation calculations intended for ASTEC V0 , but not necessarily until mid 1998
- * : global validation calculation for PHEBUS FPT0, FPT1, perhaps TMI2 which serves simultaneously as demonstration calculations

First results of validation (ELSA module)

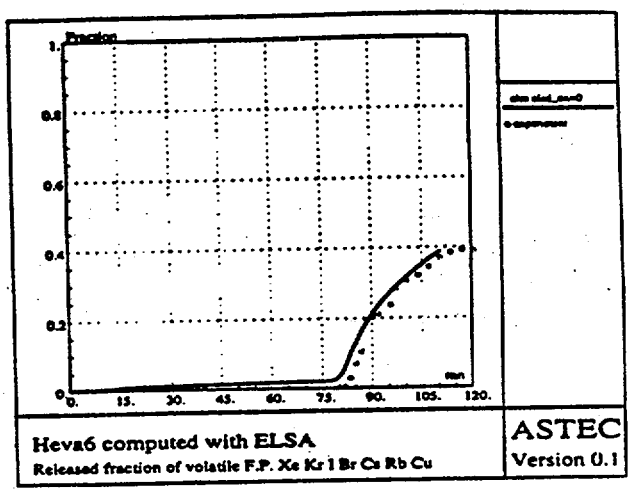
VERCORS4 experiment (IPSN program): influence of a reducing atmosphere (H2) on aerosol and FP release; fuel temperature up to 2300°C,

- good agreement on the volatile FP release (kinetics and total release).

HEVA-6 experiment (IPSN program): similar test conditions (except fuel temperature up to 2075°C) and validation conclusions.



VERCORS4 computed with ELSA
Released fraction of volatile F.P. Xe Kr I Br Cs Rb Cu

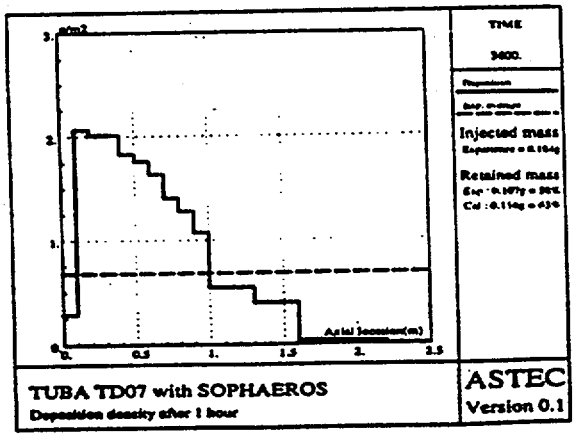


Heva6 computed with ELSA
Released fraction of volatile F.P. Xe Kr I Br Cs Rb Cu

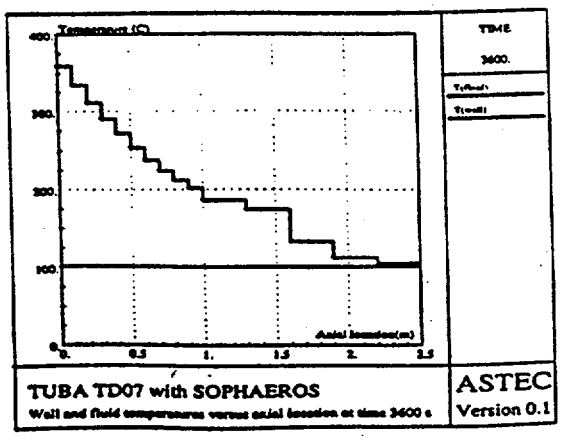
First results of validation (SOPHAEROS module)

TUBA-D: IPSN experiments for diffusiophoretic retention in a SG pipe:

- injection of a steam-helium mixture with CsI aerosols,
- results of the application to the TUBA-D TD07 experiment (see graphs below, where only the average experimental deposition value is available):
  - good global agreement on condensation (72.3% / 74.6%) and on retention (63% / 58%)
  - contribution: diffusiophoresis 94%, thermophoresis 6%.



TUBA TD07 with SOPHAEROS
Deposition density after 1 hour



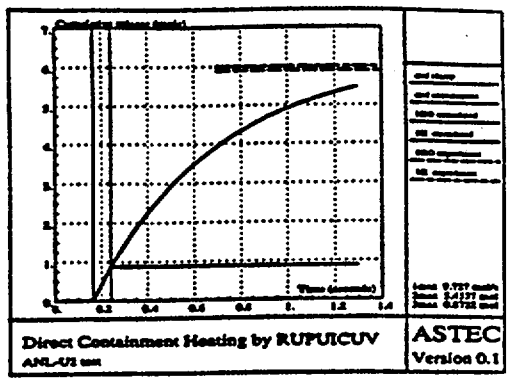
TUBA TD07 with SOPHAEROS
Wall and fluid temperatures versus axial location at time 3600 s

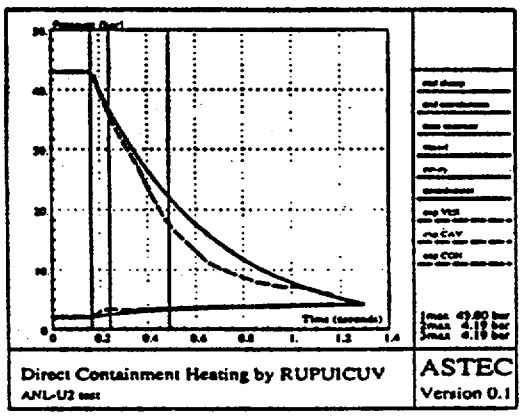
First results of validation (RUPUICUV module)

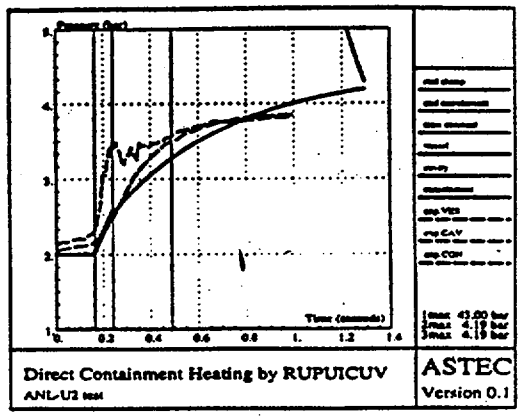
ANL DCH tests in Zion geometry at 1/40 scale, with prototypical corium,

good agreement on pressure: vessel blow-down and increase in cavity,

good agreement on cumulated steam mass, but under-estimation of H2 production (short entrainment duration and under-estimation of oxidation).







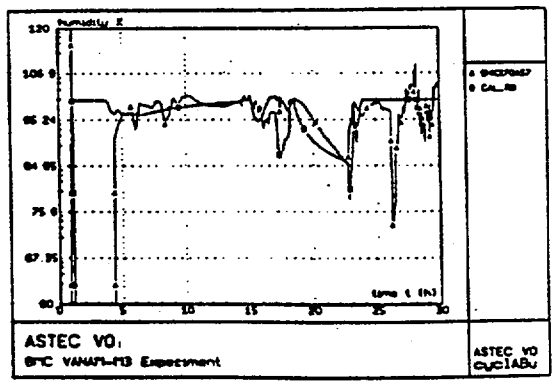
First results of validation (CPA)

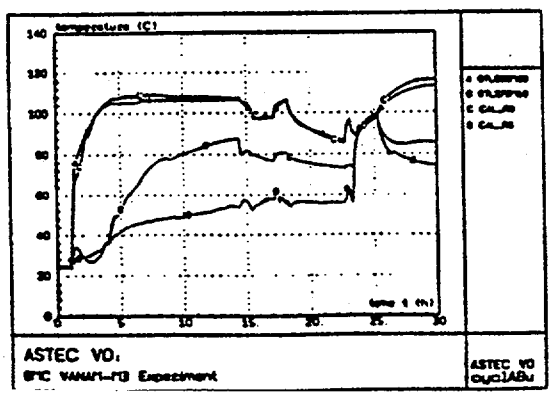
VANAM: thermalhydraulic and aerosol program,

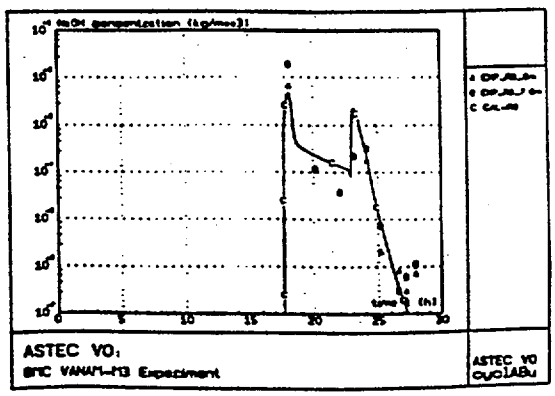
- M3 test (ISP 37): injection of steam, air and aerosol into a multicompartment containment.

CPA results:

- good agreement on temperatures, except for the lower room R6 (need for splitting of R6).
- good agreement on humidity with the non-equilibrium model, but problems in the annulus zones.
- good agreement on the dry and wet aerosol depletion.







FPT0 application

Focused up to now on the bundle degradation phase (VULCAIN code).

Modelization (similar to ICARE2 and MAAP4 ones):

- 2 x 11 meshing (control rod only in the 1st ring),
- characteristics of the surrounding structures issued from ICARE2 calculations.

Satisfactory global agreement on the sequence of events, and particularly:

- on fuel clad rupture (with Chapmann correlation),
- on Zry oxidation (H2 produced mass and kinetics),

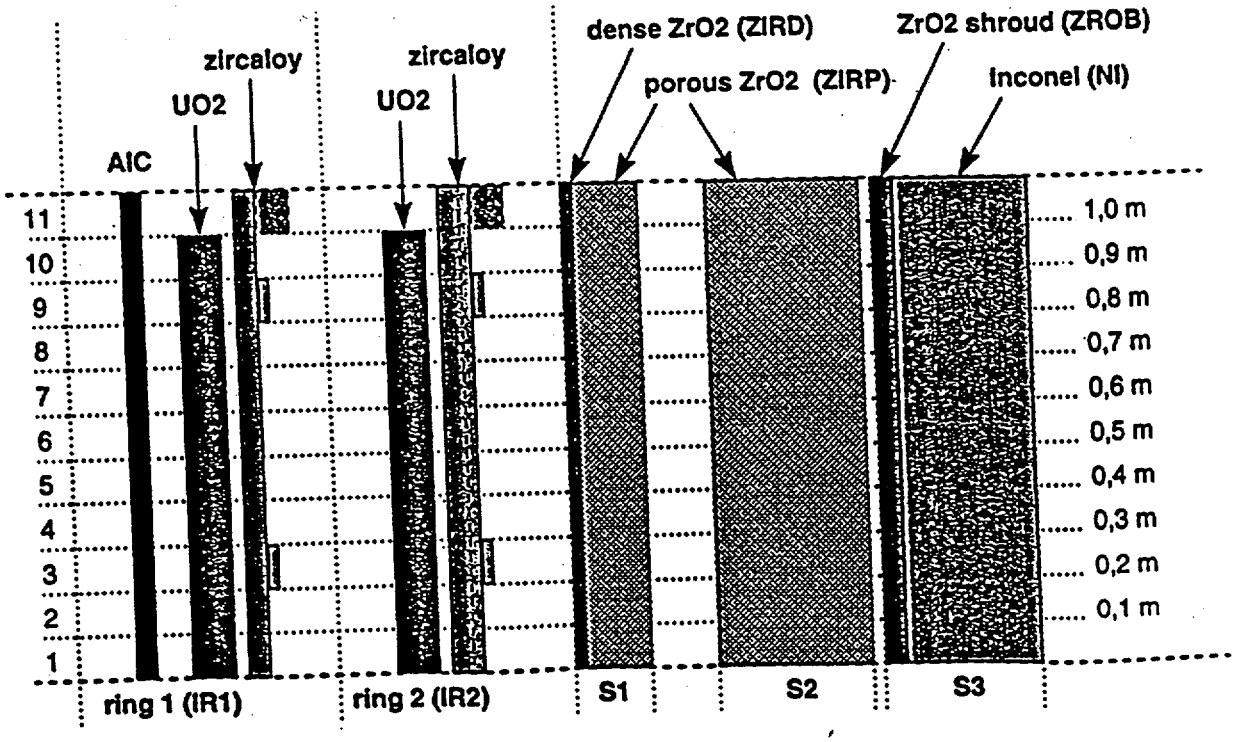
But discrepancies on :

- chronology: delays on control rod rupture and on fuel rod collapse, and thus on molten pool formation.

Chronology (s)	fuel rod clad failure	control rod failure	ZrO2 relocation	UO2 relocation	molten pool formation
Calculation	6940-7180	11920	14940	15210	16150
Experiment	6960	10788	first material movements from 14000		15180

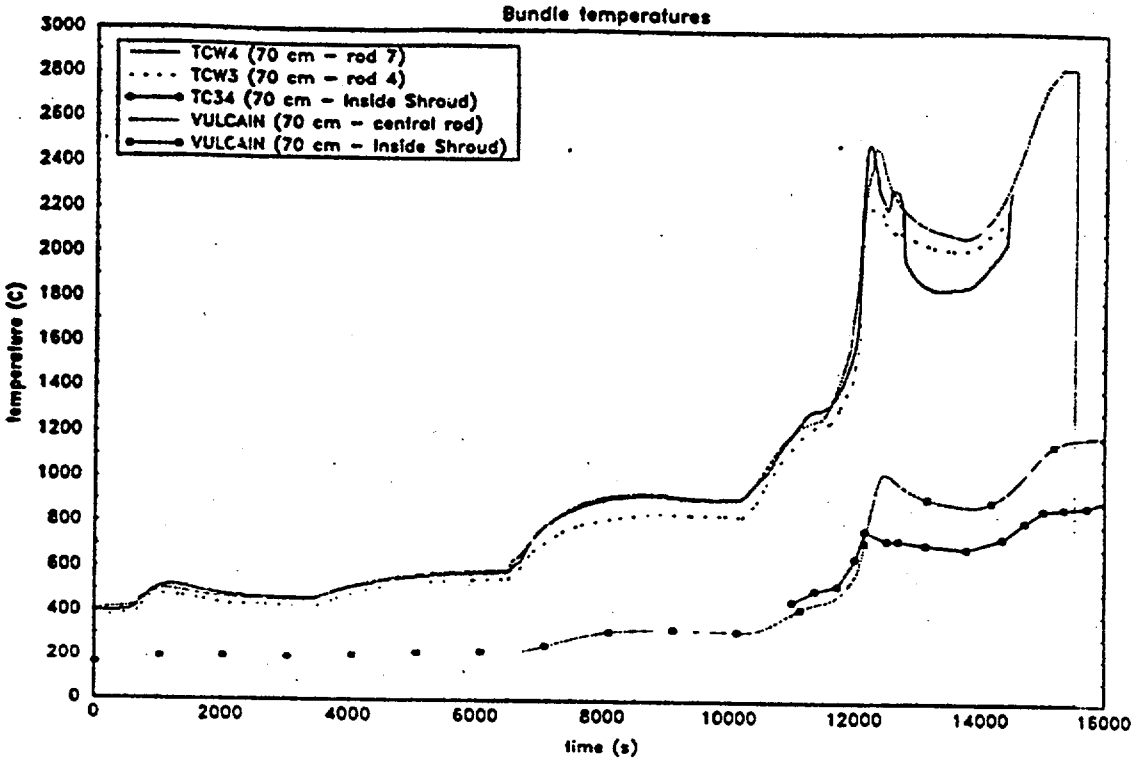
First ASTEC applications to PHEBUS FP

FPT0 core nodalization (VULCAIN)



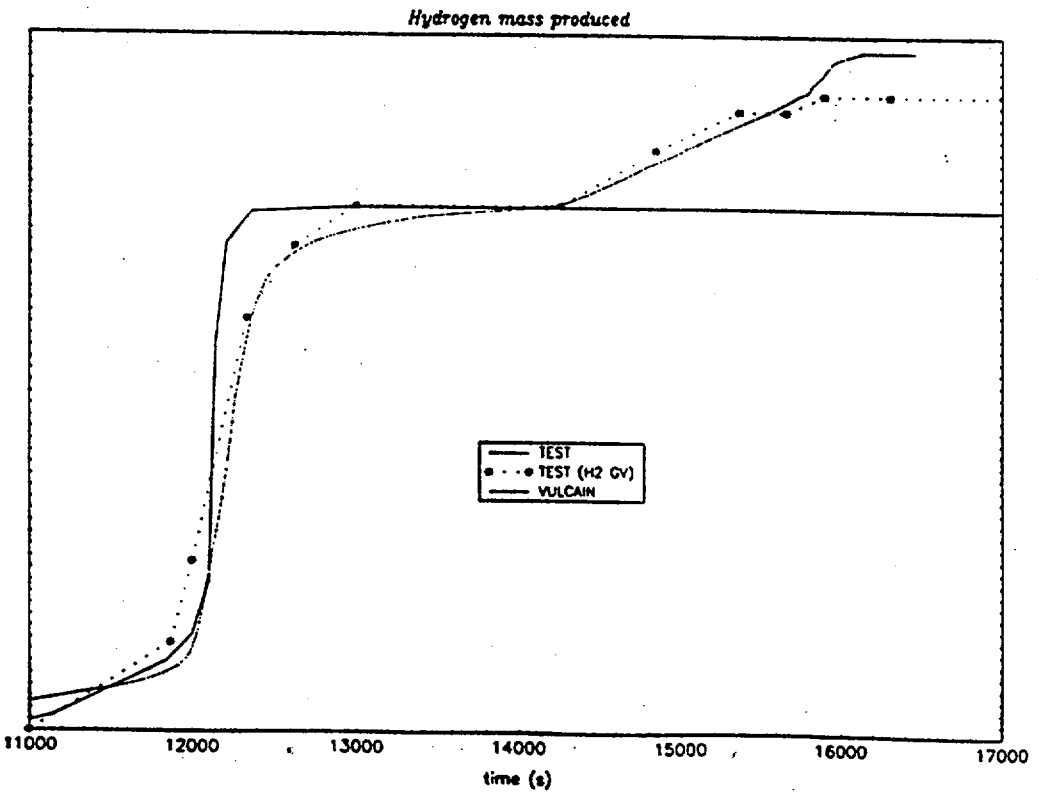
First ASTEC applications to PHEBUS FP

ASTEC V0 – VULCAIN 7.1 code – PHEBUS FPT0 test



First ASTEC applications to PHEBUS FP

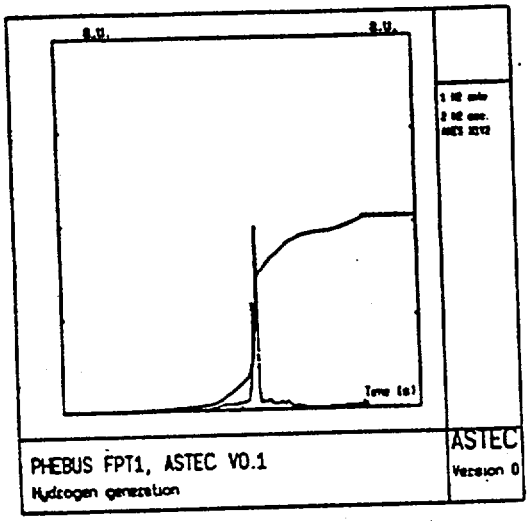
ASTEC V0 – VULCAIN 7.1 code – PHEBUS FPT0 test

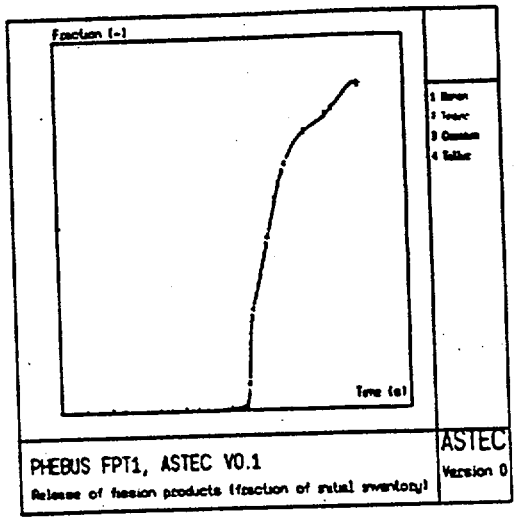


FPT1 Hydrogen and FP release

slight over-estimation of the calculated H2 produced mass: discrepancy 7% (VULCAIN code),

correct calculation of the total volatile FP release (ELSA-VULCAIN codes).



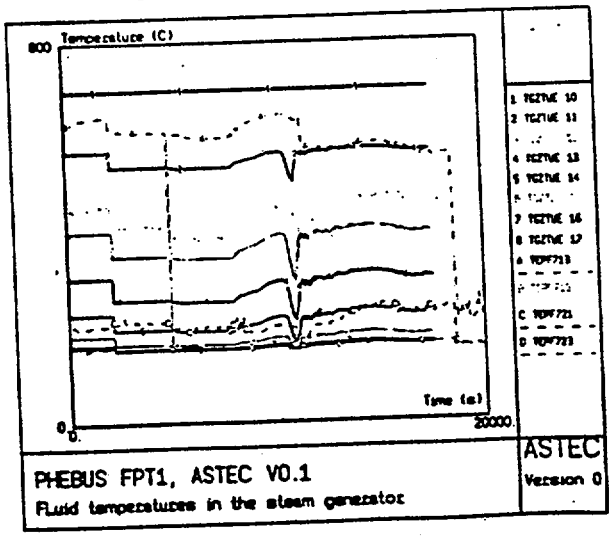


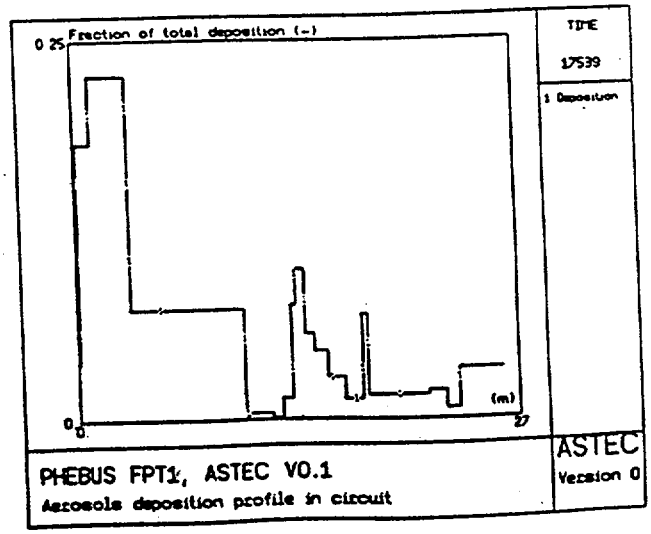
FPT1 transport and deposition

good global agreement on the calculated SG fluid temperatures (VULCAIN - SOPHAEROS codes).

two calculated zones of significant FP deposition by thermophoresis: bundle exit and SG,

- *but the deposition profile is not yet satisfactory (interpretation to be improved...).*





FPT1 application

ASTEC V0.1 parallel applications to:

- the primary circuit (VULCAIN-ELSA-SOPHAEROS),
- the containment (thermalhydraulics and iodine parts of CPA).

☛ *coupling of the two above applications in the next future (June 98) to simulate the whole experiment.*

Same bundle modelization than FPT0 (except 22 axial meshes for the bundle), with 18 volumes for the circuit.

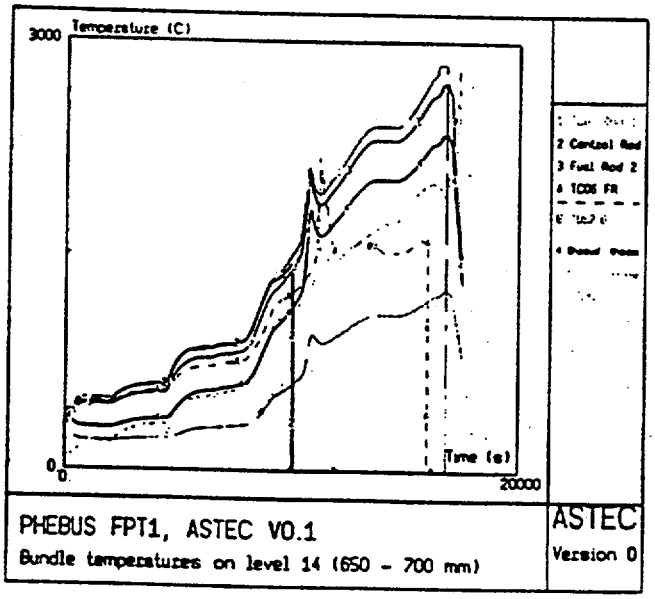
First main conclusions on bundle degradation with VULCAIN:

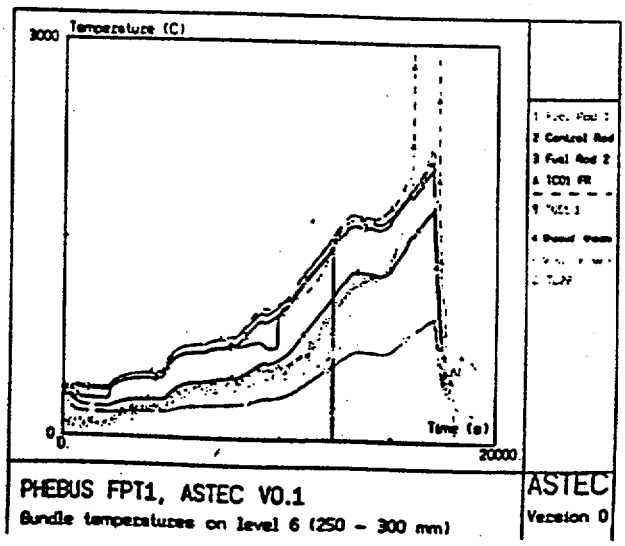
- good H2 production mass evaluation; peak slightly in advance,
- good global agreement on bundle temperatures, but in the calculation:
  - oxidation peak slightly in advance,
  - delay of fuel rod failure with the standard EDGAR model,
  - molten pool formation delayed (because of need to reach high melting temperatures).

Chronology (s)	fuel rod clad failure	control rod failure	ZrO2 first relocation	UO2 first relocation	molten pool formation
Calculation	8240	9900	16230	16490	16950
Experiment	5800	9690	material movements between 15900 and 16800		

First ASTEC applications to PHEBUS FP

FPT1 bundle temperatures





Axes of reflexion

Main foreseen improvements:

- RCS 2-phase flow thermalhydraulics during the front end and during the degradation (specifications mid-98) :
  - simplified models derived from French CATHARE code,
  - further validation against the reference codes CATHARE and ATHLET.
- new core degradation part:
  - based on ICARE2 structure,
  - models derived either from simplified ICARE2 ones or from VULCAIN.

Reflexion on the necessity of general improvement or replacement of WECHSL for MCCI.

Improvement of models (update of some constitutive modules):

- FP release for advanced degradation (ELSA 1.2),
- gas-phase chemistry, aerosol mechanical resuspension and vapour homogeneous nucleation (SOPHAEROS 2.0), and later pool scrubbing ,
- Ag/I reactions in the water sump (IODE 4.2).

Improvement of the informatic structure: ODESSA (SIGAL interface module in F90).

☛ *Schedule: end of 1999- beginning of 2000.*