Crud Deposition Studies in the Cirene Loop

Technical Progress

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ABSTRACT

Crud deposition on the fuel under the sub-cooled boiling condition plays an important role in the AOA phenomenon observed in many PWRs. Investigators are performing out-reactor tests in the Cirene loop with the objective of obtaining rates of crud deposition as a function of known steaming rates, coolant chemistry (pH, Li/B levels) and bulk Fe, Ni concentrations.

The Cirene loop consists of four full-length electrically heated Zircaloy rods, and simulates PWR conditions closely except for the irradiation flux. A series of tests lasting up to 35 effective full power days (EFPD) have been completed since mid-1998. Optional controlled injection of Fe and Ni (soluble and particulate) to the coolant was implemented in some of the tests. At the conclusion of each test, crud coverage and deposition rates were evaluated and detailed crud characterization was performed.

Data and results obtained from all tests performed under this program through late 2000 are summarized in this interim report. Unlike the accelerated testing performed in the earlier loop testing in France and UK, the test conditions in the current program were selected to represent a typical AOA core. This meant relatively lower thermal duty (steaming rates and exit voidage) and the absence of coolant oxygen while maintaining hydrogen over pressure.

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1
INTRODUCTION

The core-wide axial power offset observed in some PWRs results from local power suppression in the core. The so-called Axial Offset Anomaly (AOA) is believed to be due to concentration of boron bearing species in the crud deposited on the fuel rods. The crud deposits are generally thick and highly localized in the upper axial elevations where sub-cooled nucleate boiling occurs, especially in high duty PWR cores. Consequently, the deposition of primary-circuit corrosion products on the fuel, core thermal duty, and primary coolant chemistry play important, often synergistic, roles in onset and build-up of the AOA problem during reactor operation.

The overall goal of Robust Fuel Program Working Group 1 (Fuel/Water Chemistry) is to develop viable candidate solutions to mitigate Axial Offset Anomaly (AOA) in PWRs. An essential part of this overall effort is to conduct out-reactor loop tests to provide better understanding of sensitivity of crud deposition to operational parameters such as boiling duty and coolant chemistry. In addition, out-reactor loop tests are ideally suited for development of remedial measures to control crud. Therefore, a test program was undertaken jointly with EDF and CEA, in the Cirene loop facility in France. The loop simulates typical PWR core conditions except for the radiation flux. The Cirene loop has a 2x2 full-length rod bundle representing a typical PWR fuel assembly geometry. The 'fuel' rods, fabricated of Zircaloy cladding tubes, are heated electrically.

1.1 Background

The current program of out-reactor loop tests is not the first of its kind. The EDF/Framatome/CEA/Westinghouse sponsored crud studies program performed between 1978-86 was also carried out in the same facility (the Cirene loop at CEA/Cadarache). This "old program" had a large stainless steel surface area in the loop circuit and the tests were conducted under aggressive conditions of high void fraction. The crud generated in this program was mostly ferrous oxide type; not the Ni-rich crud that is considered responsible for AOA. The control of coolant oxygen and hydrogen over pressure might not have been strictly enforced in the previous program. These attributes were purposefully addressed in the current test program to represent AOA type core conditions.

Since the "old program", EDF has been conducting radionuclide transport studies in Cirene loop. The loop has been also modified recently with Inconel heat exchangers tubes.

Concerning crud deposition in the Cirene and the Bihan loop, the following general observations have been noted based on the experience:

- more iron rich deposit form when void fraction increases;
- the crud structure is influenced by boiling;
- presence of chimneys (of ~ 2 μm of diameter) in the crud deposits (~20 μm) observed under boiling conditions (max. void fraction ~10%);
- presence of chromium observed in the crud;
- with injection of soluble nickel and iron, thick crud deposits (~20 μm) form after 80 to 90 days of operation;
- tendency to form thicker crud below grid locations of the test rods.

1.2 Objectives

Specific objective of the current test program is to obtain fundamental data on characteristics and rates of crud deposition under nucleate boiling conditions.

The critical data needs are in the following areas:

- dependence of crud deposition on boiling duty;
- influence of coolant pH on crud deposition under boiling conditions;
- dependence of both particulate and soluble species in the coolant on the crud deposition;
- relation of the observed high Ni/Fe ratios in the AOA plant crud on crud deposition and morphology

The testing began in mid-1998. This report is an interim report on the tests completed by late 2000.

1.3 Approach

From the beginning, the researchers envisaged a three-step test program summarized as follows:

Step 1: The purpose of Step 1 was to demonstrate system capabilities. The aim was to ascertain that it would be possible to deposit representative AOA-type crud in the Cirene loop, with particular emphasis on conducting tests under non-aggressive and non-accelerated conditions. Four such tests were performed and are reported in Chapter 3.

Step 2: The objective of Step 2 was to acquire crud coverage and deposition rate data as a function of T/H duty, coolant pH, and external ion injection. Two such tests were carried out *without external ion injection* and are reported in Chapter 4. Subsequently, three additional tests were carried out *with external ion injection* (Chapter 5).

Step 3: Pending successful completion of Step 2, this final step has not yet been initiated. Step 3 is anticipated to begin in 2001. The originally foreseen plans for Step 3 are as follows:

(a) Expand on Step 2 with additional tests as needed

(b) Include additional (new) probes and instrumentation to improve in-situ diagnostics

(c) Study in-situ boron deposition in crud

(d) Specifically try-out AOA remedies such as enriched boric acid and potassium hydroxide

Examples of the improved in-situ diagnostics under (b) may include: (1) in-situ visualization of crud and voids; (2) in-situ pressure drop measurements; (3) in-situ diameteral probe to measure crud thickness at power, (4) XRD and Raman Spectroscopy of crud scraps; (5) effect of radiolysis by local γ-source (in the Corail loop).

2
EXPERIMENTAL

2.1 Description of the Cirene Loop

The Cirene loop aims at simulating PWR core conditions. A schematic diagram of the loop is shown in Figure 2-1. It is equipped with four electrically heated Zircaloy rods in a prototypic PWR fuel assembly geometry within a test section. The heat exchanger consists of four steam generator tubes (7/8 inch diameter tubes of Inconel). In addition, several active and inactive stainless steel and Inconel knit meshes were added to the circuit in December 1998 to modify relative surface area ratios of Inconel, Stainless Steel and Zircaloy.

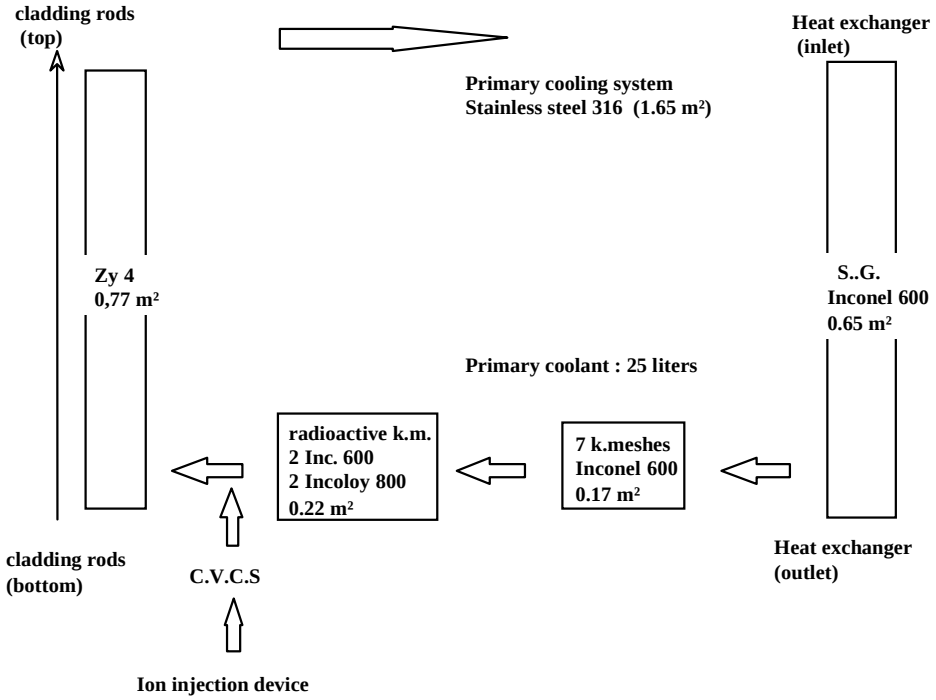


Figure 2-1
Cirene Loop Outlines

The relative surface areas in the Cirene loop are compared to those in a typical 3-loop PWR in Table 2-1. The surface area of stainless steel dominates in the Cirene loop relative to the desired PWR values. Due to practical limitation of pressure drop, more knit meshes could not be arbitrarily added to the circuit. From another perspective: Inconel 600 area (which is the main corrosion products source term in a PWR) is around 15000 m^2 for a 200 m^3 volume in a three loop PWR. The volume of the Cirene loop is 25 liters. Thus to have the same Inconel area/volume ratio as in a PWR, an Inconel area of 1.9 m^2 in the loop is needed. Only half of this value is realized in the Cirene loop.

Table 2-1
Surface areas in Cirene loop compared to a 3-loop PWR

	3 - loop PWR	Cirene Loop	
		%	Total (m^2)
Zircaloy	24 %	22 %	0.77
Inconel	66 %	30 %	1.05
Stainless steel	10 %	48 %	1.65

The surface areas indicated in Figure 2-1 and Table 2-1 represent the current values in the Cirene loop. At the beginning of 1998 series test (see chapter 3), the heat exchanger tubes were *fresh* (i.e., unpassivated) Inconel 690. They were changed out to *fresh* Inconel 600 tubes at the beginning of 1999 series tests (see chapter 4). In addition, new knit-meshes were installed between the two test series in December 1998. The types of knit meshes can be summarized as follows:

1998 tests

7 unactivated Inconel 600 knit-meshes

+ 1 activated Inconel 600 knit-mesh

+ 1 activated stainless steel 316 knit-mesh.

1999 tests onwards (current status)

the same 7 unactivated Inconel 600 knit - meshes

+ 2 new activated Inconel 600 knit - meshes

+ 2 new activated Inconel 800 knit - meshes.

The loop is equipped with a chemical volume control system (CVCS), through which optional external ion injection could be implemented. The CVCS is typically at ambient temperature in the range of 25 to 40 °C. The system for controlled injection of soluble Ni and Fe ions is described further in Section 2.4. The CVCS by-pass flow rate is adjustable in the range of 4 to 6 liters per hour. The coolant clean-up function of CVCS through resin beds (demineralizers) was not activated in any of the tests performed, except where specifically noted otherwise, because the objective in the present test program was to maximize the crud deposition on the test rods.

Typical operational parameters are listed below. These values are interdependent through the requirement of overall heat balance. They can be varied somewhat keeping on mind the desire to represent prototypic PWR conditions

Test Section

Inlet temperature	:	311 °C
Inlet mass flow rate	:	250 g/cm^2.s
Inlet pressure	:	150 bar
Injected power	:	70 W/cm^2

Heat Exchanger

Inlet temperature	:	330 °C
Outlet temperature	:	284 °C

2.2 Test Rods

The test section consists of four Zircaloy-4 test rods (each ~ 4.28 m long) with the following characteristics:

Cladding No 1	Stress-relieved AFA 2G, electropolished;
Cladding No 2	Recrystallized Zry-4, non-electropolished;
Cladding No 3	Stress-relieved Zry-4, non-electropolished;
Cladding No 4	Stress-relieved Zry-4 non-electropolished.

The cladding tubes contain stainless steel sheathed boron nitride insulator through which a nickel-chrome heating element is installed. The ohmic heating provides the heat flux in the range of 70 to 100 W/cm^2. The average length of all the claddings submitted to the heat flux, is 1.80 m and is located between the +1.60 m and + 3.40 m axial references of the Cirene test section. Seven axial Zircaloy grids hold the 4 claddings together with the same geometrical characteristics as those of a 17x17 REP assembly.

Figure 2-2 is a sketch of a test rod indicating locations of the grids and crud scrapes (see also Section 2.5).

The geometry of the heated rod test section can be represented as follows:

Shroud perimeter	:	10 cm
External diameter of rod:	:	0.95 cm
Rod pitch	:	1.25 cm
Heating length	:	180 cm
Hydraulic diameter:	:	0.62 cm
Hydraulic cross-section:	:	3.41 cm^2

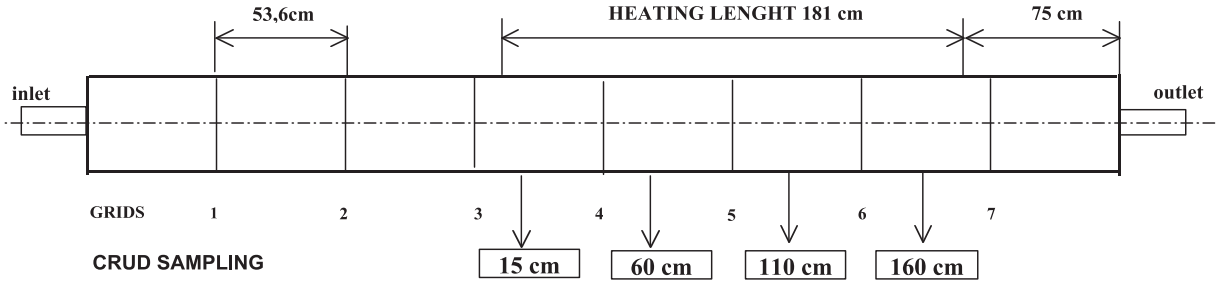


Figure 2-2
Sketch of a test rod indicating locations of grids and crud scrapes

2.3 Thermal-hydraulic Conditions

This section describes the selection of the thermal-hydraulic (T/H) conditions for the Cirene tests to obtain a desired mass evaporation rate. In order to represent prototypic PWR thermal-hydraulics, it was necessary to maintain the mass evaporation rates in the Cirene tests within the range of 1000 and 2500 kg/hr.m^2. The mass evaporation (steaming) rates are typically obtained using codes such as VIPRE-01 or FLICA.

As described later in Chapter 5, a full thermal calibration of the loop system was performed in September 2000, which concluded that evaporation (steaming) rates computed for tests 1998/01 through 2000/02 are subject to certain systematic bias. The actual evaporation rates may be ~15% lower than those reported in this Interim Report. The necessary corrections have not been made here.

CEA performed Cirene T/H calculations using the FLICA code (Code version 3.2). A core bundle consisting of four heating rods within an external shroud of 10-cm perimeter simulated the Cirene loop. The external diameter of one heating rod is of 0.95 cm. As an example, the main results of these simulations for 1998/01 (see Chapter 3), obtained for steady state conditions, are the following:

Average outlet void fraction : 1,7 % (subnucleate boiling conditions)

Maximum wall temperature : 344.5°C

Similar calculations were also made for other tests throughout the program.

The following steps were followed in the FLICA computation

Step 1: Estimation of the global evaporation rate

The global evaporation rate, Gvap, is linked to the evaporation flux, Φvap, by the following relation:

$$Gvap = \Phi vap/L,$$

where L is the latent heat of condensation.

The evaporation flux can be deduced by the following relation:

$$\Phi vap = \Phi.Xc$$

where Φ is the imposed flux and Xc is the local evaporation rate expressed by :

$$Xc = 1 - \frac{Tsat - Tl}{\frac{\phi}{h} - \Delta Tsat}$$

where *Tl* is the liquid temperature, *Tsat* the saturation temperature, *h* the heat transfer coefficient for convection and *ΔTsat* the temperature difference between wall and saturation.

Step 2: Estimation of the net evaporation rate

The net evaporation rate, Nvap, is the difference between the global evaporation rate and the bulk condensation rate. It is also related to the mass flow rate G and the quality, X, by the following relation :

$$Nvap = G\ \Delta X\ \Delta z$$

where ΔX and Δz are respectively the quality difference and level difference along the vertical axis (flow direction).

Figure 2-3 represents calculations performed for test 1998/01. The evaporation rates obtained in this test - 500 to 1900 kg/m² hr - are in a good agreement with the desired range 1000 to 2500 kg/m² hr.

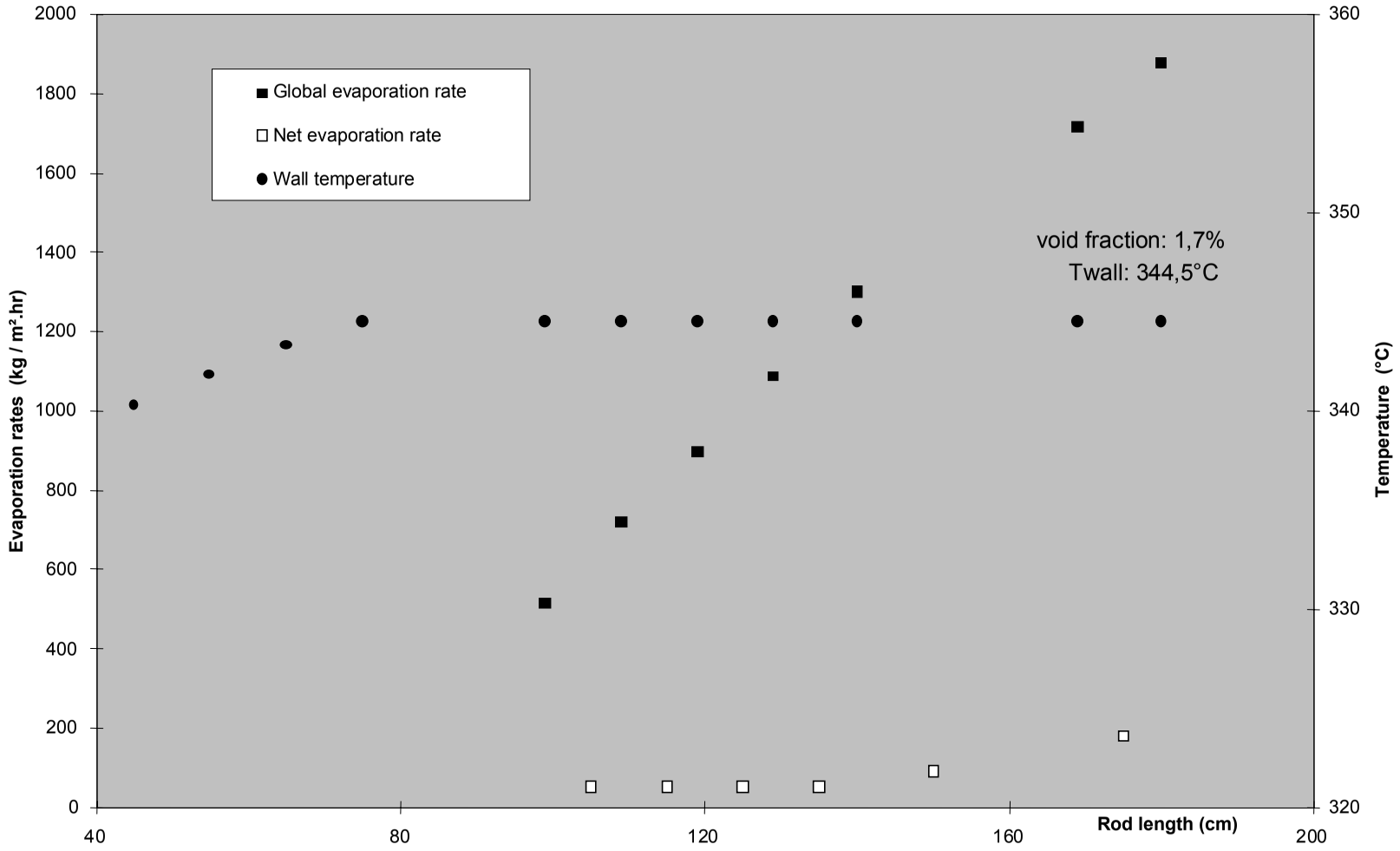


Figure 2-3
Evaporation Rates in Cirene Loop, Average Channel Subnucleate Boiling Conditions

2.4 External Ion Injection

A system to inject iron and nickel ions into the primary circuit of the Cirene loop was developed to achieve thicker crud deposit in reasonable time-scales (1 to 2 months duration test). The device is shown in Figure 2-4. The injection was also deemed necessary to reproduce the concentrations of metallic elements released into the primary circuit of the PWRs. The external injection option was activated starting from 2000 series of tests (see Chapter 5).

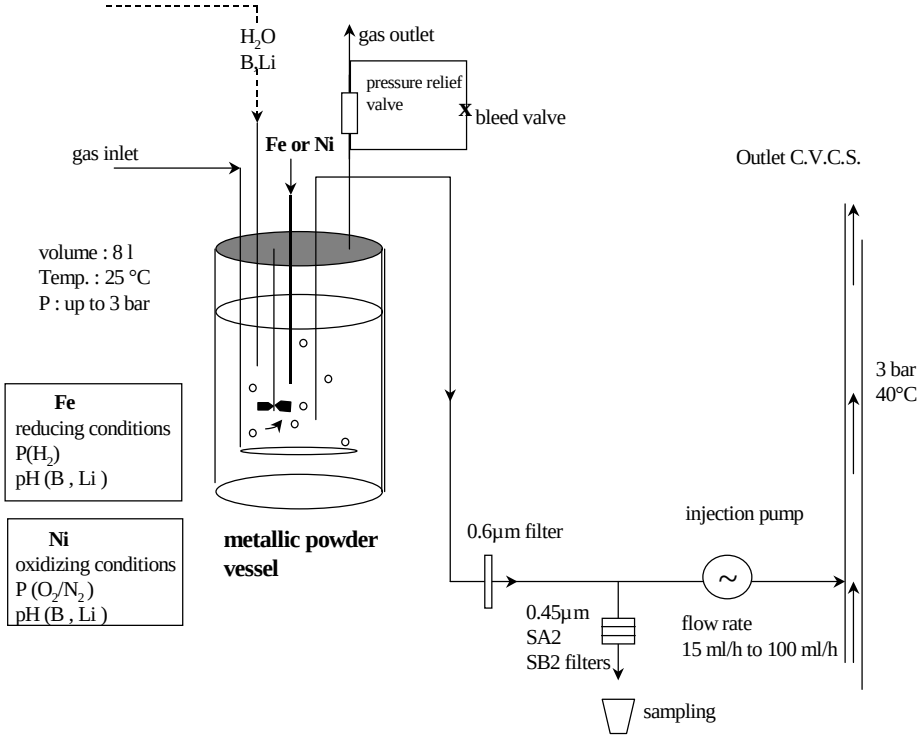


Figure 2-4
Cirene Loop – Ion Injection Device

Operating principle and purpose of the injection system

The plan involved continuous injection of two solutions of dissolved iron and nickel, prepared independently from one another. Injection occurred at ambient temperature, and at ~3 bar, upstream of the charging pump, at the outlet of the CVCS circuit.

The objective was to achieve a deposit of corrosion products on the fuel claddings equivalent to ~ 12 mg/dm² at the end of a 20 days test. The quantity of material injected into the primary fluid will be supplemented by the quantity of material released by the constituent materials of the primary circuit.

Experimental installation

The iron and nickel powders were dissolved at ambient temperature and at 1.5 - 2.5 bar pressure of H_2, using borated and lithinated demineralized water drawn from the main tank of the Cirene loop. The apparatus is shown in Figure 2-5.

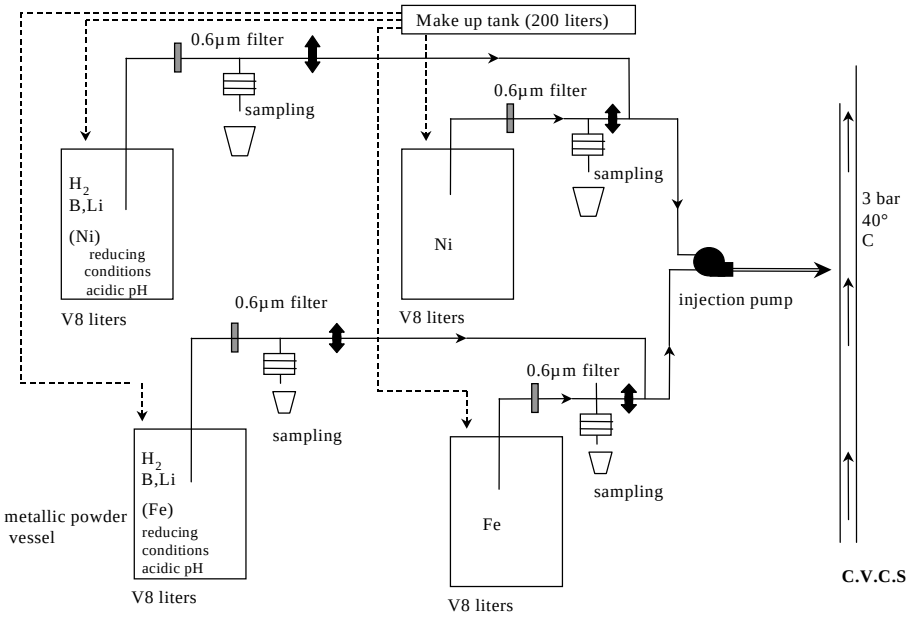


Figure 2-5
Schematic Flow Diagram of External Injection System

The following items can be identified in the Figure:

- a 8 liters capacity vessel, with an agitator, a borated, lithinated and hydrogenated water inlet, and an introduction system for the iron or nickel powders;
- a gas bubbling system (N_2, O_2/N_2 or H_2) with a pressure gauge, and an outlet gas line including a bleed valve and a pressure relief valve;
- a sampling line with a 0.6 µm porosity filter, located upstream of the analysis sampling point;
- a metering pump with 2 pump heads, regulated at a specific flow rate for each vessel, located upstream of the charge pump at the CVCS outlet.

Preparation of the metallic solutions

As shown in Figure 2-4, vessels containing Ni and Fe solutions are connected to CVCS line through a metering pump. Both vessels are in duplicate to maintain uninterrupted dosing throughout the test duration.

Ni vessel:

An oxidizing medium was established at the solubility level for nickel at ambient temperature and in an acid medium, i.e. around $0.85.10^{-4}$ and $2.5.10^{-4}$ mol/kg. The nickel concentration in the vessel was, therefore, at a level between 5 and 15 mg/l. The pH of the solution will be determined by the boron and lithium content in the main supply tank water, i.e. $pH_{25°C} = 6.3$ with [B]=1000 ppm and [Li]=1 ppm.

Fe vessel:

A reducing medium was established at the solubility level for iron at ambient temperature and in an acid medium i.e. around $0.5.10^{-4}$ and $1.5.10^{-4}$ mol/kg. The iron concentration was, therefore, at a level between 3 and 8.5 mg/l. The pH of the solution will be determined by the boron and lithium content in the main supply tank water, i.e. $pH_{25°C} = 6.3$ with [B]=1 000 ppm and [Li]=1 ppm.

To maintain a Ni/Fe ratio of ~4 in the quantities of iron and nickel injected during the test, a specific setting for each of the head pumps was required. The injection flow rates are also related to the total volume of the RCS (25 liters), and a maximum leakage rate to be established in the primary circuit, to permit this continuous injection. For example, a 20 day test and with injection flow rates set at G_{Ni} = 45ml/h and G_{Fe} = 15 ml/h, the total volume injected becomes 29.5 liters which induces a continuous " leak " of ~ 1.5 l/day for the installation.

Analyses

The dosing of iron and nickel was performed for each preparation vessel based on samples taken downstream of the 0.6 µm porosity filter (see Figure 2-5). The samples are passed through a 0.45 µm Millipore filter and two ion-exchanger filters (anionic SB2 and cationic SA2) to quantify the soluble and particulate proportions in metallic elements. Filters analyses were performed by X-ray fluorescent spectrometry. Limited ion chromatography analyses were performed to quantify the contaminating elements present in the preparation vessels.

2.5 Crud Coverage and Characterization Methods

If sufficient crud was present at the end of a test, it was characterized in the following manner:

gamma scanning along the rods

scrapping (weight, chemical analysis, structural analysis)

chemical dissolution of crud to analyze (Li, Mg, Ca, Si, Fe, Ni, Cr, Co, oxygen)

In principle, isotopes released from the activated stainless steel 316 and Inconel 800 knit-meshes can be measured by gamma scanning the test rods. The radioactivity profile of either the whole bundle or individual test rod was performed through gamma-ray spectrometry at the end of the test. Subsequently, crud scrapings from one of the four test rods were collected on filter papers from a length of about 20-cm at the 15, 60, 110 and 160-cm axial elevations (as shown in Figure 2-2). The crud scraping locations in Figure 2-2 were in the middle the scraped length. The end of the 20-cm scraped length was to the next grid downstream.

In some cases, rod was gamma-scanned *after* such scraping and the activities of certain isotopes collected on the filter papers were measured as well. The collected crud scrapings were also subjected to a chemical analysis through wavelength X-ray fluorescent spectrometry by the chemistry laboratory (LARC) of CEA/Cadarache.

2.6 Coolant Chemical Analyses

Primary fluid samples were taken at suitable times during operation of the each test. The following analyses were performed:

(a) boron, lithium

(b) metallic species : Fe, Ni, Cr, Mn, Zr, by X-ray fluorescence (2 liter sample)

(c) impurities : Na, K, Mg, Ca, Al, SiO_2, F^-, Cl^-, SO_4^{2-}, by plasma

(d) oxygen and hydrogen were monitored through probes in the CVCS

Analyses (b) and (c) were conducted at a chemistry laboratory (LARC) of CEA/Cadarache. The samples were passed through a 0.45 µm filter and ion-exchanger filters (anionic filters SB2 and cationic filters SA2) to increase measurement sensitivity, and to quantify the ion and particle proportions. At the end of each test, a coolant sample of the isolated test section at 60 °C was taken and analyzed. (The volume of the isolated test section is 2.2 liters.)

The analyses involved coupling plasma emission spectrometry, atomic absorption spectrometry, and ionic chromatography. Metallic elements were analyzed by X-ray fluorescent spectrometry.

2.7 Loop Clean-up

The primary loop (isolated section, CVCS, etc.) was routinely purged between any two tests thereby minimizing the chances of crud transfer or release of trapped material from one test to another.

3
1998 SERIES TESTS

3.1 Operation and Results

Four tests, designated as 1998/01 through 1998/04, were completed in 1998. They were conducted with equivalent thermal-hydraulic and coolant chemistry parameters, as summarized below:

Coolant inlet temperature	311 °C
Coolant outlet temperature	347 °C
Pressure	15.5 MPa
Global steaming rate	1000 to 2500 kg/hr/m^2
[Li] and [B]	2.2 and 2000 ppm (pH = 6.7 at 310 °C)
[H2]	30 cc/kg (no oxygen addition or in-leakage)

The purpose was to obtain at least 5 μm of crud that is representative of AOA type crud without external ion injection or high boiling duty. The thickness of the crud was not a strict requirement as long as crud coverage was measurable with reasonable confidence in the data. A Ni/Fe ratio of > 1 was anticipated in the crud, based on the crud analysis from Callaway plant.

A s summarized in Table 3-1, the test 1998/01, which had a scheduled hot-shutdown, resulted in a maximum residual crud deposit of 9 mg dm^{-2} crud in 11.5 days. This is equivalent to < 1 μm of crud at the conclusion of the test. Two subsequent tests 1998/02 and 1998/03 experienced unscheduled hot shutdowns after 9 and 10.5 days, respectively, and produced only ~ 0.8 mg dm^{-2} of crud deposit. The last test 1998/04 had a scheduled cold shutdown after 34 days. Since hydrogen peroxide was injected in test 1998/04, crud burst and crud dissolution is to be expected. All these tests had the same chemistry, viz., Li at 2 ppm and B at 2000 ppm. The estimated crud thicknesses in Table 3-1 are based on the theoretical density of 1.2 g/cm^3 in the sub-cooled nucleate boiling area on the cladding. Test 1998/03 experienced an unexpected copper contamination in the coolant due to a faulty heating rod, and as such, it will not be analyzed further.

The concentrations of [Li]= 2.2 and [B]= 2000 ppm, were chosen for the following reasons:

- Resulting operation at pH300 °C = 6.7 increases fuel deposit (in comparison with operating at a pH300 °C above 7.0)

- Crud deposits on fuel rods often occur in long cycles with high initial boron concentration above 1500 ppm.
- Tests performed in the CORELE loop show an increase of the Inconel 600 release rate with the Boron concentration

Table 3-1: Summary of Tests Completed in 1998

TEST	1998/01	1998/02	1998/03	1998/04
Coolant Chemistry	[Li] = 2.2 ± 0.1 ppm and [B] = 2000 ± 50 ppm			
EFPD (separate for each test)	11.5	9	10.5	34
Shutdown	Scheduled; rapid	Unscheduled; rapid	Unscheduled; rapid	Scheduled; cold
Visual Inspection	Brown-yellow color	No notable color	Results unreliable; not analyzed further	Light-brown color
Photographs	Yes	No		No
Max. crud coverage (mg/dm^2)	~ 9	~0.8		~ 1
Max. crud thickness (μm)	~ 0.8	~ 0.07		~0.1
Remarks	Heat exchanger tube passivation	-	Faulty heating rod; Copper intrusion	Crud dissolution

The coolant Ni and Fe concentration values in Cirene loop during these tests were lower than typical values in PWR plants. This may have been due to the high inlet temperature (311 °C) and the retrograde solubility of Ni and Fe. Some of these values were even under the detection thresholds of the chemical analysis:

1998/01 test - normal operation; Fe < 2.5 ppb and Ni < 1 ppb

1998/02 test - normal operation; Fe < 1 ppb and Ni < 0.4 ppb

1998/03 test - normal operation; Fe < 1 ppb and Ni < 0.4 ppb

1998/04 test - normal operation; Fe < 1 ppb and Ni < 0.4 ppb

The following points are also noteworthy in 1998 series tests:

(1) The observed residual crud coverage all four these tests was very low. It was neither possible to obtain crud deposition rate data reliably nor adequate crud samples for XRD and Mossbauer analyses. The limited crud that could be sampled was analyzed by X-ray

fluorescence to deduce Ni / Fe ratios. Four new Inconel heat exchanger tubes were installed (change out from original stainless steel tubes) before the start of test 1998/01. Since four new activated knit-meshes (Inconel 600 + Inconel 800) were added after completion of test 1998/04, the surface area ratios were slightly different from those in Table 2-1. *During* 1998 series tests, the relative surface areas were as follows:

Inconel	26%
Stainless steel	51%
Zircaloy	23%

(2) The cladding tubes were cleaned after each test in 1998; thus, each new test began with the same 4 claddings but without any deposited crud from the previous test. This procedure was discontinued after 2000/01 test to accumulate and preserve the crud on the rod surface. In the subsequent test in 2000/02, the crud was allowed to build-up, except for a small section of one tube that was scraped to obtain crud coverage and analysis at the end of each test.

(3) The high initial crud deposition rate (9 mg/dm² in 11.5 days in test 1998/01) could be due to fresh Inconel heat exchanger tubes without surface passivation. With exposure to the coolant, the corrosion product release rate from these tubes was expected to stabilize.

3.2 Cold Shutdown in Test 1998/04

As outlined in Table 3-2, the scheduled cold shutdown in 1998/04 was conducted as follows: Cool down at the rate of 50°C / hour from 311°C to the ambient temperature with two temperature plateaus, one at 170°C, the other at 60°C after the H_2O_2 injection in the primary coolant.

Table 3-2: Scheduled cold shutdown routine in test 1998/04

Primary coolant temperature	311°C	holding temp. 170°C	80°C	holding temp. 60°C
Pressure	155 bar			61 bar
Chemistry conditions	[Li] = 2.2 ppm [B] = 2000 ppm [H_2] = 25-35cc/kg	sampling for chemical analysis	H_2O_2 injection	sampling for chemical analysis

[O_2] = 2 ppm in the make up tank

To determine the deposits on fuel before shutdown, it is necessary to consider:

- Deposit remaining on fuel after shutdown (scraping)
- Deposits which are dissolved during shutdown (coolant activity)

Indeed the plant data indicate that the deposits observed on fuel rods after shutdown are affected by the shutdown procedures. The Co58 activities and Ni corrosion product mass measured during shutdown period in primary water are mainly from the fuel rod deposits. No significant release of deposits on stainless steel or Inconel surfaces occurs during shutdowns. Figure 3-1, based on over 50 data points from various French plants, makes this point.

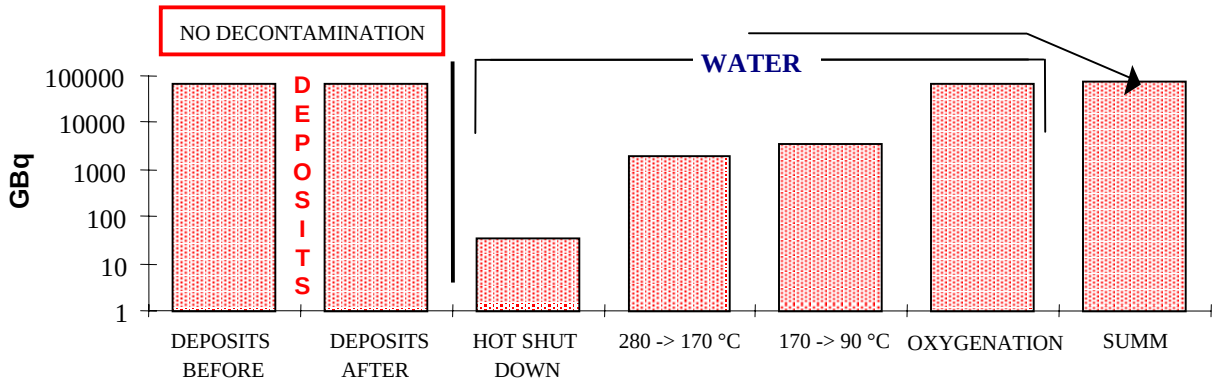


Figure 3-1
Activity Release During Shutdown (Co58)

The Ni/Fe ratio of deposit before shutdown can be estimated from such measurements.

Typical values in French PWRs, without AOA, are the following:

	Remained deposit	Removed deposit	Total
Ni/Fe	1.3	23	4

The results from 1998/04 (Figure 3-2 and 3-3) show that the average ratio Ni/Fe in the scraped crud after aeration is around 1. This is consistent with values seen from crud scrapes in France as well as in Callaway Cycle 6 and Millstone Cycle 4. The calculated Ni/Fe ratio in the Cirene crud *before shutdown*, taking in account the metallic species released to the coolant of the isolated test section during the aeration, was around 6.

The objective in 1998 test series was to prove that it was possible to obtain deposits similar to those observed in plants in terms of Ni/Fe ratio and to show the effect of oxygenation during shutdown. Figures 3-2 and 3-3 show that expected characteristics were met. Subsequently, since it was desirable to preserve crud on the test rods, the H_2O_2 injection was no longer applied in subsequent testing in 1999 and 2000.

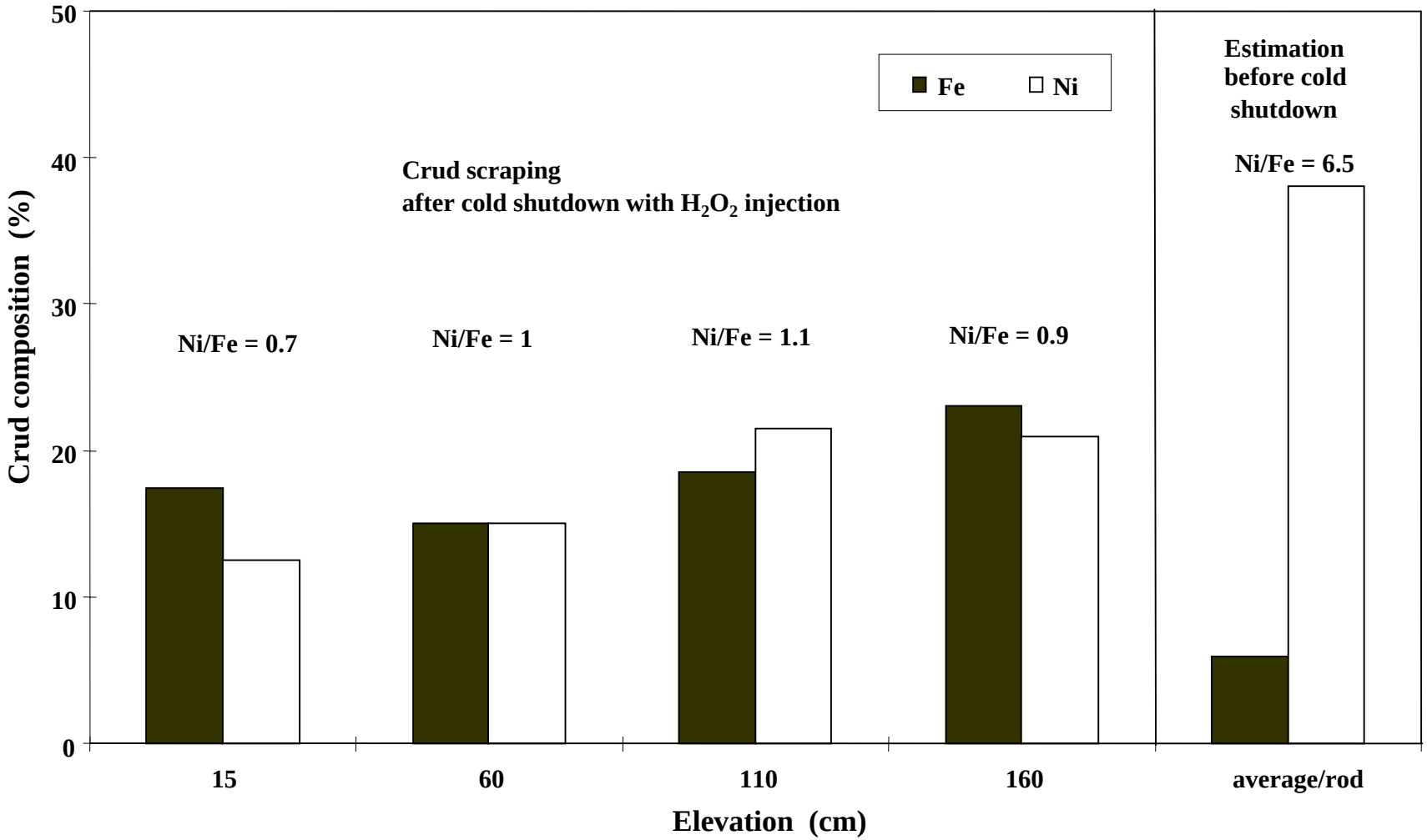


Figure 3-2
Crud Deposit on Cladding Rod – Cirene Test 1998/04, Chemical Composition Analysis (X Ray Fluorescence)

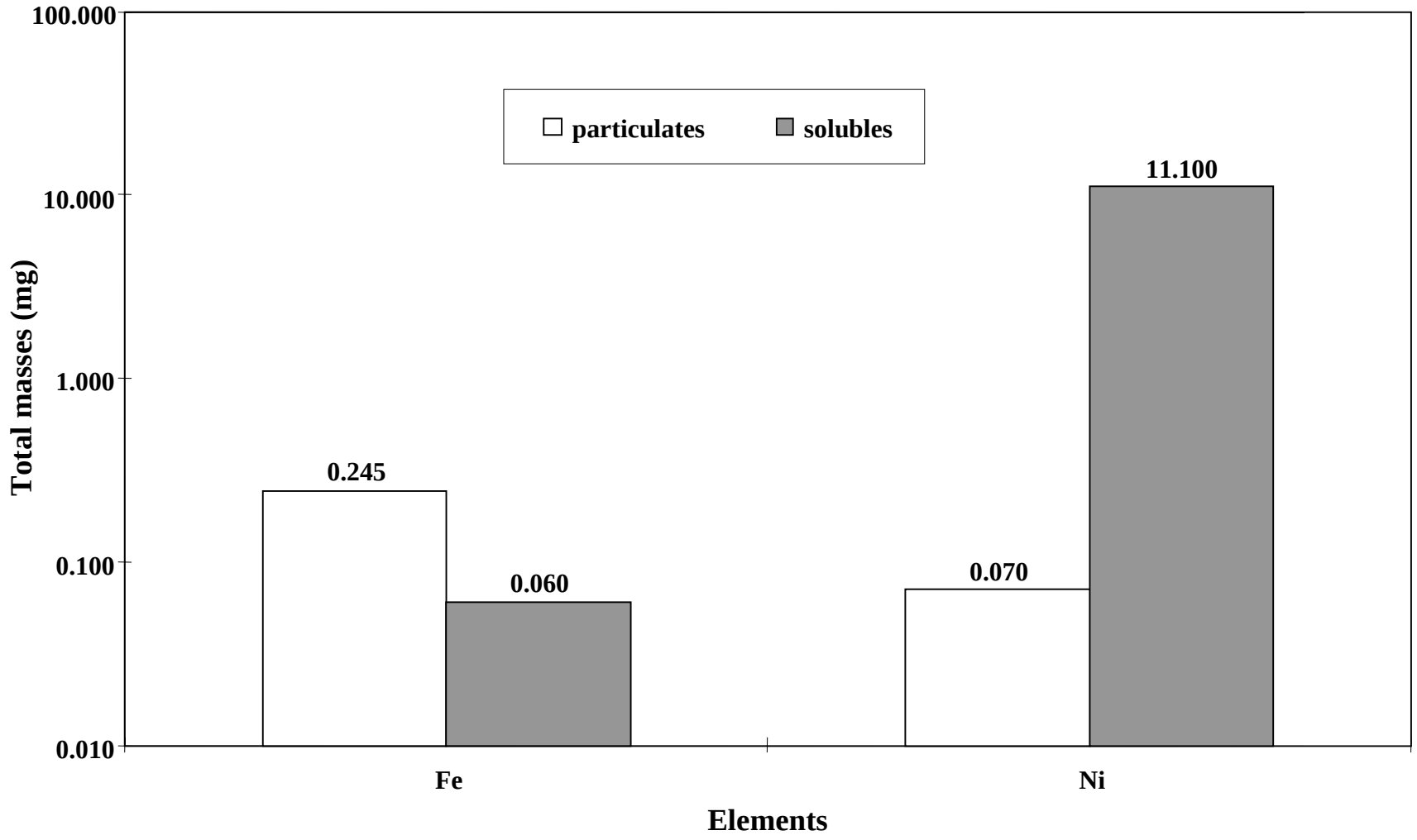


Figure 3-3
Fe and Ni Masses in the Test Section Isolated At 60°C After the H_2O_2 Injection - Cirene Test 1998/04

3.3 Discussion

The stainless steel (SS) part of the Cirene loop is more than 15 years old. The long term release rate for this material is around 0.5 mg/dm^2/month (Taylor, "Review of the available data on the release transport and deposition of corrosion products in PWR, BWR and SGNWR Systems", AERE.R.8164, 1976, p 38; Cohen, "Water coolant technology of power reactors", New York, 1969, p 439). By contrast, the components made of Inconel are less than one year old, the common release rate for this material is around 1 or 2 mg/dm^2/month. In a test of one month in duration, a release of 80 mg from the SS area and 140 mg coming from the Inconel area is expected. The gamma spectrometry measurement performed on the heat exchanger tubes in the Cirene loop show an increase of the Co58 and Co60 deposited activities. This means that deposition occurs not only on the heated rods but also in the other part of the loop. If we consider a uniform deposit in the loop (3.37 m^2), we will obtain a deposit of 0.65 mg/dm^2. In case of preferential deposition on the heated rods only, we can obtain a deposit around a few mg/dm2/month to be compared to the 1.8 mg/dm^2 obtained on the rods during test 1998/04. If the release is proportional to alloy constituents, the Ni/Fe ratio should be 1.7.

4
1999 SERIES OF TESTS

4.1 Test 1999/00

4.1.1 Purpose and Procedure

The purpose of this test was to get a certain level of passivation for the new Inconel 600 heat exchanger tubes and the knit meshes that were added in December 1998, after the conclusion of test 1998/04. This was deemed necessary before any subsequent testing for crud deposition because of the large release rate from then new Inconel 690 heat exchanger tubes in test 1998/01. Accordingly, the first test of 1999, namely 1999/00, was conducted mainly to check out the functions of newly installed CVCS with required coolant analysis and radiochemical measurements performed during and after the test.

The duration of test 1999/01 was 29 EFPD (from 3/31/99 to 4/29/99) with the following chemical conditions:

[B]=1 000 ppm

[Li]=1 ppm

[O_2]=2 ppb (in the make-up tank)

[H_2]=30 cm^3/kg

The boron level was reduced in 1999 series tests to 1000 ppm while maintaining the same pH.

The thermal-hydraulics conditions of 1999/00 were representative of the environment of a Belleville 2, where AOA was observed during Cycle 5. A comparison of the two is given in Table 4-1.

During test 1999/01, a leakage was detected at the source holder. This prevented the intended primary fluid circulation over the radioactive knit-meshes. Therefore, gamma scans were not performed upon completion of this test.

A 6 l/hr flow rate in the CVCS, *with* ion exchange resins, was set to trap soluble corrosion products during the test. The test was concluded with a scheduled rapid shutdown, with the fluid temperature decreased at a rate of 30°C/hour, including one temperature plateau at 60°C to take coolant samples.

Table 4-1
1999/00 Test Condition compared to Belleville Cycle 5

PARAMETERS	BELLEVILLE	CIRENE LOOP TEST 9900
Pressure (bar)	155	150
Inlet mass flow rate (g/cm² s)	384	250
Test section inlet temperature (°C)	294	300
Test section outlet temperature (°C)	328	331
Max. cladding wall temperature (°C)	347.1	344.5
Heat flux (W/cm²)	30 - 86	75
Average exit void fraction	0.1 %	0.6 %
[B] ppm	1000	1 000 +/-50
[Li] ppm	2	1 +/- 0,1
pH (300°C)	7	6.7
[H_2] cc/kg	40	25 - 35
[O_2] ppb	< 5	< 5 ppb
C.V.C.S flow rate		6-8 liters per hour
Duration		about 30 EFPD

4.1.2 Results

At the conclusion of the test, once the system cooled down to ambient temperature, Cladding No. 2 was scraped on filter papers (25 mm diameter) over a length of about 20 cm (i.e. about 60 cm^2) at 15, 60, 110, and 160 cm axial elevations in the heated section. Of these, the scrapings taken at 110 and 160-cm elevations were subjected to chemical analysis through X-ray fluorescent spectrometry.

Table 4-2
Results of a semi-quantitative analysis of all the elements, given in µg/filter after test 1999/00

Axial elevation	110 cm	160 cm
Analysis No.	73 152	73 151
Na	< 70	< 70
K	< 20	< 20
Al	< 40	< 40
Si	< 40	< 40
Ca	< 20	< 20
Mg	< 50	< 50
Fe	< 5	23
Ni	4	24.5
Cr	4.5	18.5
Co	< 2	< 2
Mn	1.5	2
Cu	< 3	< 3
Zn	4.5	4.5
Zr	120	170

Detection limits (given in µg/filter)

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zr	Zn
Detection Limits	5	1	1	1	1	3	50	1

Table 4-3 gives direct impurity analysis of the primary coolant after 10 EFPDs.

Table 4-3
« Direct » Analysis of Primary Fluid in test 1999/00 (the results are given in mg/l)

Elements	SO_4	Cl	F	Na	Al	Ca	K	Mg	Si
73221/22	0.06	0.13	< 0.01	< 0.05	< 0.01	0.013	< 0.05	< 0.01	0.14
Specifications	< 0.15	< 0.15	< 0.15		< 0.1	< 0.1			< 0.1

Table 4-4 gives direct impurity analysis of the primary coolant after shutdown at 60 °C

Table 4-4
« Direct » Analysis of the Primary Fluid at 60°C (the results are given in mg/l)

Elements	SO_4	Cl	F	Na	Al	Ca	K	Mg	Si
73229/30	0.08	0.08	0.01	< 0.05	< 0.05	0.09	< 0.05	0.4	0.13
Specifications	< 0.15	< 0.15	< 0.15		< 0.1	< 0.1			< 0.1

Table 4-5 gives analysis of primary fluid at 60 °C after it has passed through 0.45µm, SA2 and SB2 filters

Table 4-5
Analysis of the Primary Fluid at 60°C through Filters in test 1999/00 (the results are given in µg/liter and were obtained from the filtration of 2 liters.)

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zr	Zn
0.45µm Filter / 73226	45	13.5	19	0.7	1.2	1.5	< 25	< 0.5
SA2 Filter / 73227	< 2.5	27	< 0.5	4.7	36	2.8	< 25	5.2
SB2 Filter / 73228	< 2.5	<0.5	< 0.5	< 0.5	< 0.5	< 1.5	< 25	< 0.5

Detection limits given in µg/filter

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zr	Zn
Detection Limits	5	1	1	1	1	3	50	1

4.1.3 Discussion

The primary fluid analysis and the "crud" samples taken at the end of the test show that the resins in the CVCS did actually trap the corrosion products during the loop operation at full power. The mass balance performed at the end of the 1999/00 test gives about 4.4 mg of corrosion products in the primary fluid (particle and ionic forms), and about 0.4 mg of residual deposits on the 4 claddings. This represents an average "crud" thickness of ~ 0.25 mg/dm² obtained at 29 EFPD before the shutdown. This can be compared to 3.5 mg/dm² obtained before the shutdown for the test 1998/01, which was carried out with four new exchanger tubes (Inconel 690), but without primary fluid circulation through the resins mixed-bed.

Table 4-6
Comparison of conditions for tests 1999/00 and 1998/01

CIRENE test	1999/00	1998/01
Duration (EFPD)	29	11.5
4 fresh exchanger tubes	Inconel 600	Inconel 690
Heat flux (W/cm²)	75	70
Inlet temperature (°C)	300	311
[B] / [Li]	1 000 / 1	2 000 / 2
$pH_{300°C}$	6.7	6.7
CVCS.	6 l/hr flow rate with ion exchange resins	no circulation
Shutdown	rapid scheduled	rapid scheduled
Pressure : 150 bar - Mass flow rate : 250 g/cm^2.s - Wall temperature : 344.5 °C		

X-ray fluorescent spectrometry gives the following iron, nickel and chromium contents for the crud scrapings taken from the upper part of the cladding No 2:

Sampling area	110 cm	160 cm
Fe	< 21%	30%
Ni	17%	32%
Cr	19%	24%

The Fe/Ni ratio of about 1 after the shutdown is consistent with the expectation.

4.2 Test 1999/01

4.2.1 Purpose and Selection of Test Conditions

Because of the low crud coverage observed in the tests conducted so far, the conditions for the next tests, namely 1999/01, were selected to obtain the highest thermal duty *without external ion injection*. The purpose of the 1999/01 Cirene loop test was to determine the effect of the thermal-hydraulic environment on the deposit formation onto the fuel cladding. Various combinations of T/H parameters, including non-uniform heat fluxes in the four test rods, were analyzed by the FLICA code to select the conditions giving the highest steaming rate, taking into

account the system limitations in the Cirene loop. Further details and various FLICA case studies are reported in Appendix A. Stated briefly: by applying an average mass flow of 230 $g/cm^2.s$ in the test section, with an inlet temperature of 307°C and a constant heat flux of 75 W/cm^2 applied on each heating rod, a global evaporation rate of about 2 560 $kg/m^2.hr$ could be obtained (0.07 $g/cm^2.s$) in the outlet hot sub-channel (axial elevation of 180 cm).

Table 4-7 compares the test parameters in two such cases proposed, respectively, by the investigators at EPRI and CEA/EDF. The conditions finally selected for test 1999/01 are also listed.

Table 4-7
A comparison of thermal-hydraulics and chemical condition proposed for test 1999/01

	EPRI	EDF/CEA	1999/01
Pressure (bar)	140	145	143
Mass flow rate (g/cm^2 s)	225	200	230
Inlet temperature (°C)	310	305	307
Outlet temperature (°C)	337	339	337.5
Heat flux (W/cm^2)	75	75	75
Exit steaming rate ($kg/m^2.hr$) hot sub-channel	~ 2 560	~ 2 630	~ 2 530
[Li] ppm	1 +/- 0.1		
[B] ppm	1 000 +/- 50		
[H_2] cm^3/kg	25 - 35		
[O_2] ppb	< 5		
C.V.C.S. flow rate	6 - 8 l/hr		
Duration (planned)	~ 40 EFPD with rapid scheduled shutdown		

Figure 4-1 shows the calculated steaming rate as a function of axial elevation for the conditions selected for test 1999/01. The steaming rate reaches ~ 2530 $kg/m^2.hr$ at the exit. The maximum wall temperature corresponds to ~ 341°C (see Appendix A and Figure 4-2).

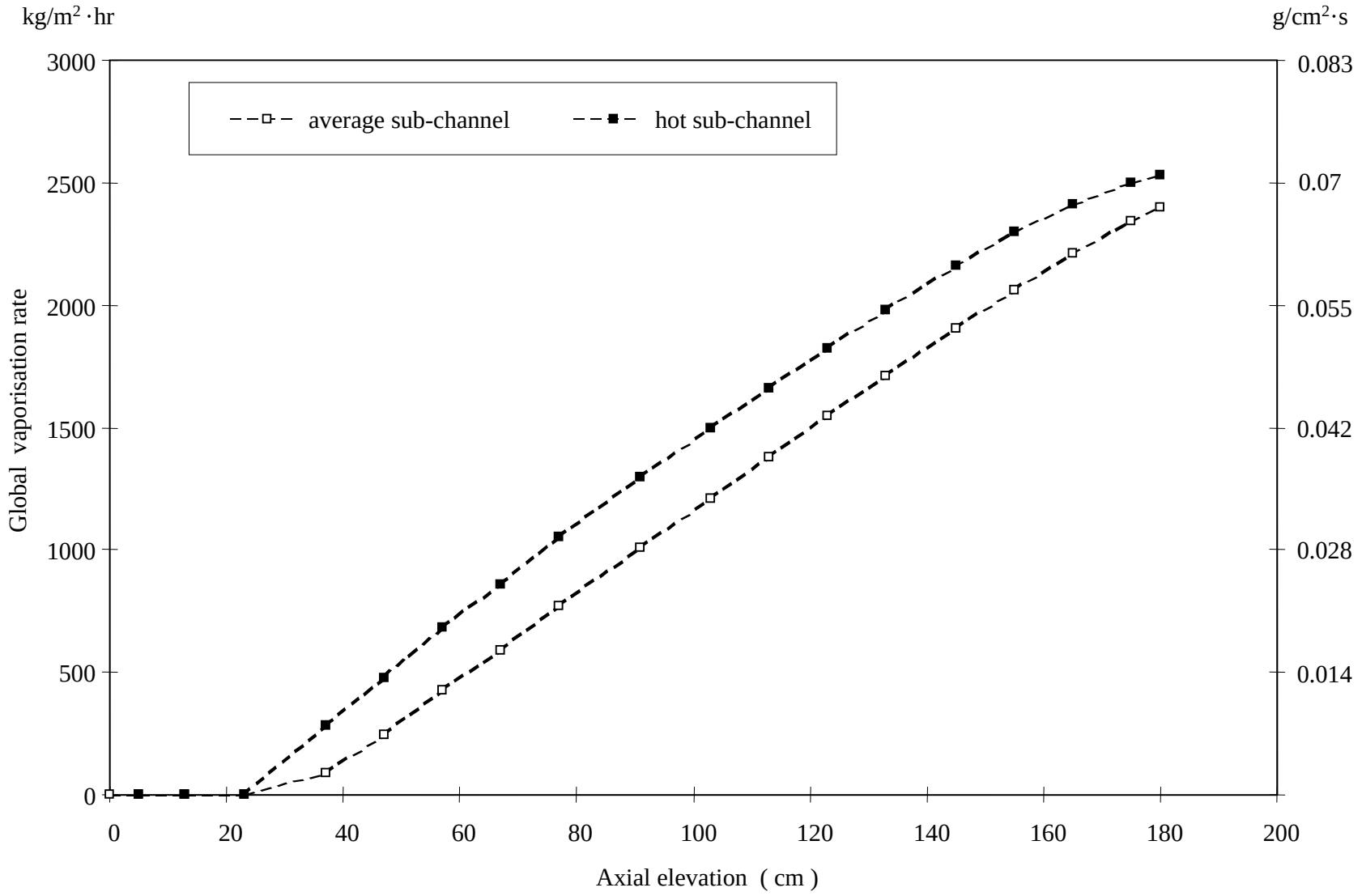


Figure 4-1
Global Vaporization Rate 1999/01 Cirene Test

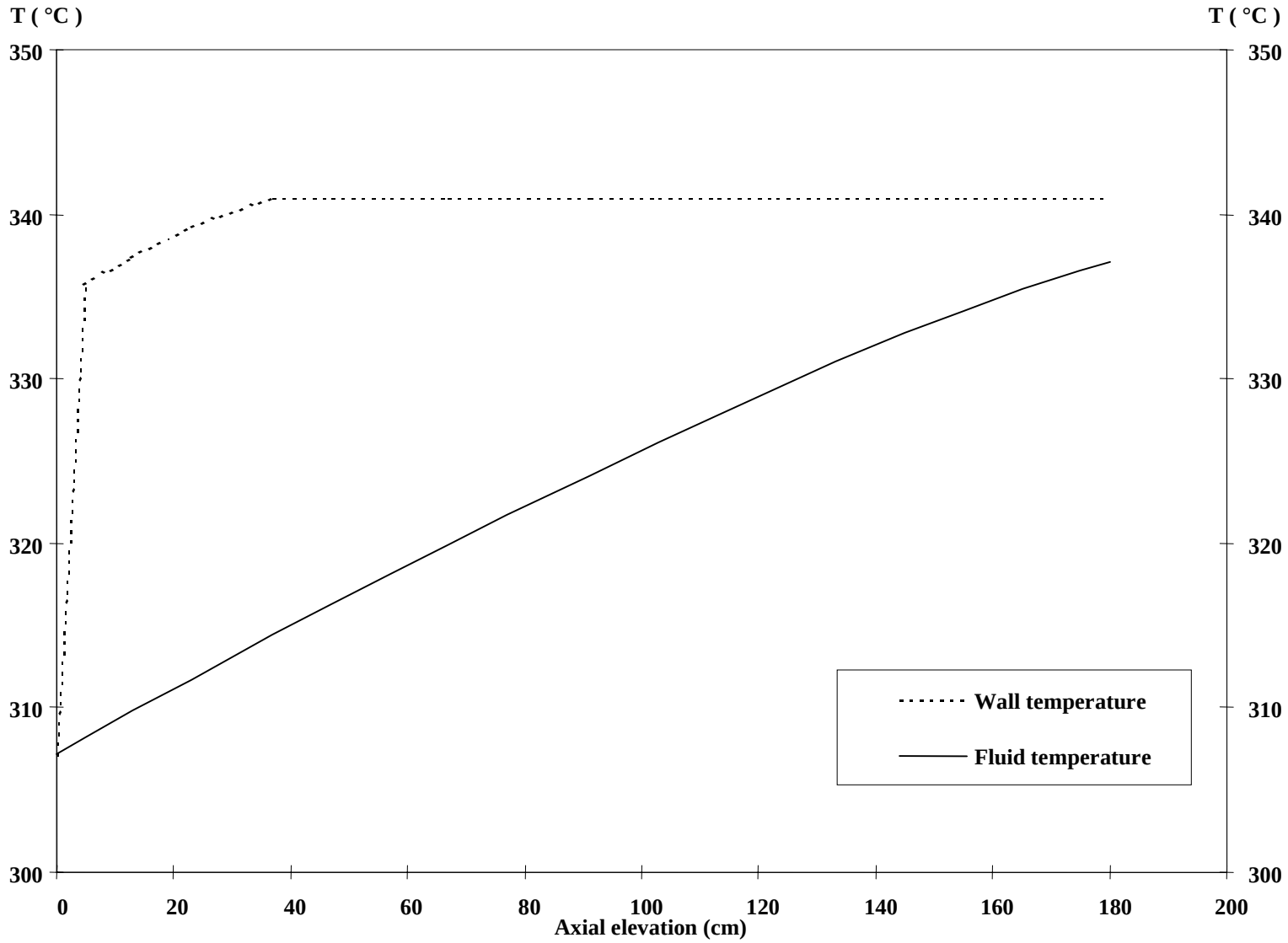


Figure 4-2
Fluid and Cladding Wall Temperatures in 1999/01 Cirene Test – average sub-channel calculations

4.2.2 Test Operation

1999/01 test was carried out (from 6/8/99 to 7/19/99) with a 4 l/h flow rate in the CVCS that was used only for the H_2 and O_2 primary fluid conditioning. There was no circulation on the ion exchange resins, unless adjustment for primary fluid conditioning in boron and lithium was required. The following operational aspects are also noteworthy :

(a) It was necessary to replace cladding rod # 4 with a fresh one of the same kind at the start of the test.

(b) The heat exchanger tubes consisted of 4 non-electropolished, heat-treated Inconel 600 tubes taken from the same industrial manufacturing batch. This exchanger had been set up in the Cirene loop in March 1999 (replacing the Inconel 690 tubes of 1998 series of tests) and therefore had an exposure totaling 29 EFPD at the beginning of 1999/01 test.

(c) At the beginning of the test, during chemical conditioning adjustment period the primary fluid lithium concentration reached 1.7 ppm, exceeding the target value of 1.0 ± 0.1 ppm.

(d) After a few days of operation at full power, the primary fluid hydrogen content determined from the CVCS was $[H_2]_{20°C\text{-}30°C}$ = 50 - 60 cc/kg. The CVCS circulation rate was then about 6 l/hr. In order to adjust the specified value of $[H2]_{20°C\text{-}30°C}$ = 30 - 40 cc/kg and lower the CVCS circulation rate to about 4 l/hr, the primary circuit had to be cleaned with nitrogen for several hours.

Oxygen and hydrogen concentrations in the primary fluid were monitored from the CVCS: during the first 30 EFPD. Figure 4-2 and 4-3 show typical sampling taken during several hours on the 2nd of July. The O_2 and H_2 levels were maintained in the specification range, i.e. $[O_2]$<5 ppb, $[H_2]$= 35 - 45 cc/kg.

1999/01 test had to be stopped with an unscheduled shutdown after 35 EFPD because of a major electrical defect in the system. The fluid temperature decreased at a rate of 20°C/h, which corresponds to a rapid shutdown. A sampling of the primary fluid was taken at 60°C for analysis.

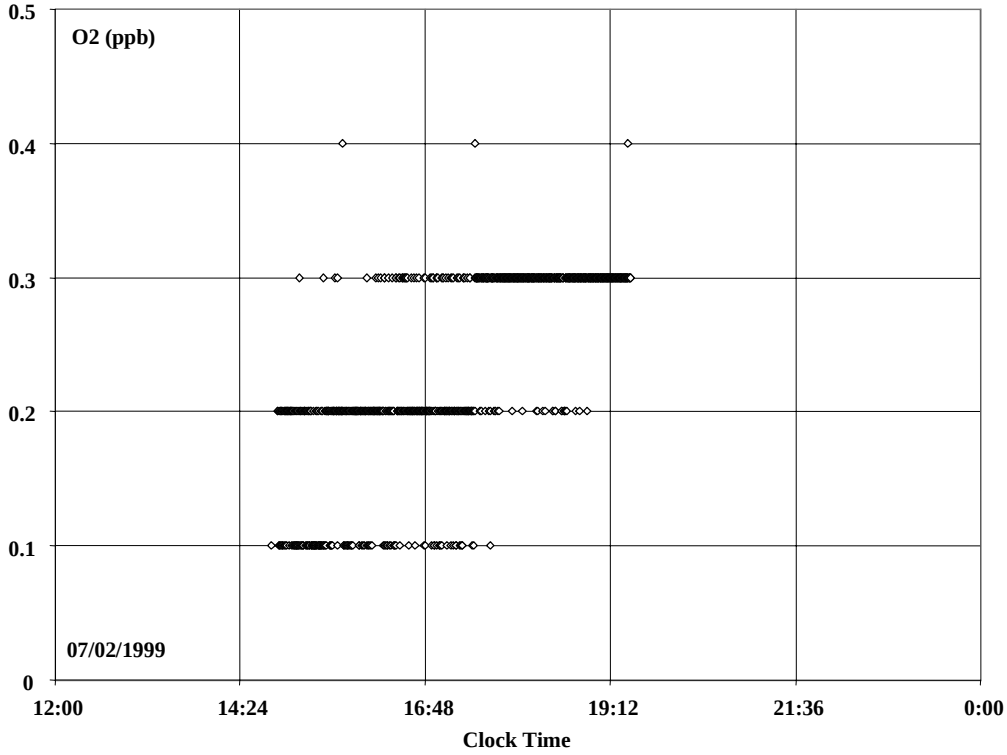


Figure 4-3
O_2 Concentration in The Primary Fluid - 1999/01 Cirene Test

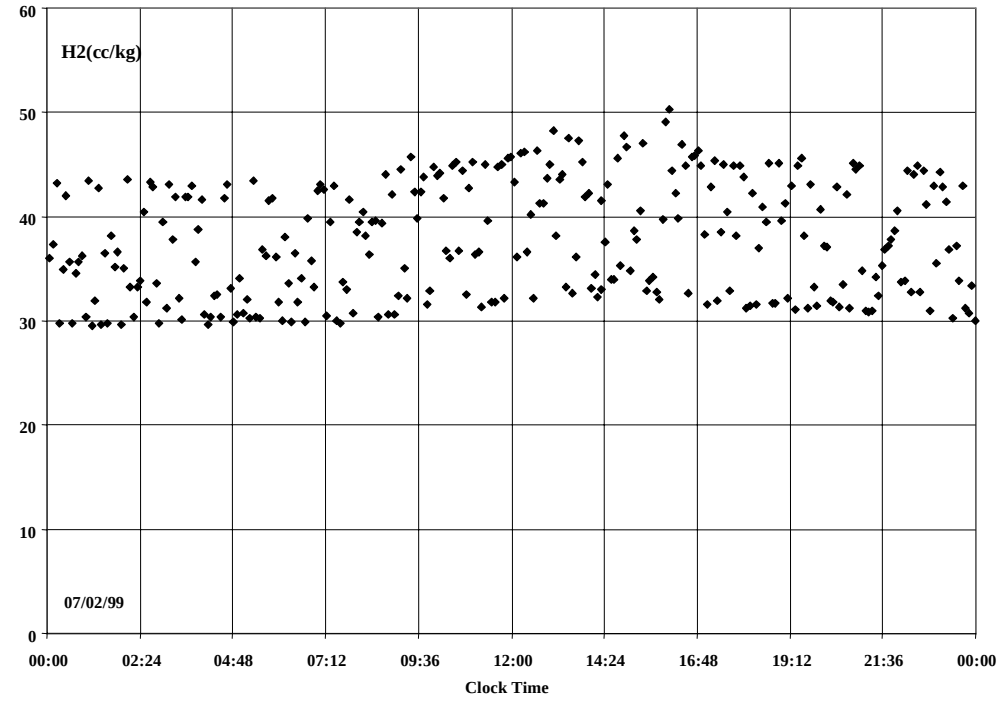


Figure 4-4
H_2 Concentration in The Primary Fluid - 1999/01 Cirene Test

4.2.3 Results

After the shutdown at 35 EFPD, the original metallic brightness of the Zry-4 claddings was no longer present, and a homogeneous, gray stain was detected all along the claddings. Gamma Scanning performed after test 1999/01 on Cladding No. 4 indicated that the crud deposits were very thin. Before scraping of the rod for crud analysis, while some ^{58}Co activity could be detected on the cladding surface, activities of ^{54}Mn, ^{51}Cr, and ^{60}Co were not detectable. No detectable activity of any of these isotopes existed on the cladding surface *after* crud scraping or *in the crud scrapings* taken from cladding.

Table 4-8 gives semi-quantitative chemical analysis of « crud » scraping from Zry-4 rod No. 4 after test 1999/01 using wavelength scattering, X-ray fluorescent spectrometry. The metallic elements contents obtained through filtrations (see Table 4-10) proved to be below the detection limits of X-ray fluorescent spectrometry analysis, except for the following elements Mn, Cu and Zn, whose contents are close to 1 to 2 µg/l.

Table 4-8
Crud Scraping Analysis (Data are given in µg / filter)

Axial elev.	15 cm	60 cm	110 cm	160 cm
Analysis No.	73 279	73 278	73 277	73 276
Fe	< 5	< 5	6,5	< 5
Ni	< 1	< 1	< 1	< 1
Cr	< 1	< 1	1,7	1
Co	< 1	< 1	< 1	< 1
Mn	1	1,3	1,4	1,5
Cu	< 3	< 3	< 3	< 3
Zn	26	15	9	12
Zr	250	190	170	140

Detection limits (given in µg / filter)

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zr	Zn
Detection limits	5	1	1	1	1	3	50	1

Following the established procedures for coolant analysis, the results from test 1999/01 was compiled in several tables below:

After 12 EFPD in test 1999/01

Table 4-9
« Direct » Analysis of Primary Fluid (the results are given in mg/l)

Elements	SO_4^{--}	Cl^-	F^-	Na	Al	Ca	K	Mg	Si
73 239/240	0.24	0.68	0.06	< 0.05	0.04	0.04	< 0.05	< 0.01	0.36
Specifications	< 0.15	< 0.15	< 0.15		< 0.1	< 0.1			< 0.1

Table 4-10
Analysis of Primary Fluid through filterations The results are given in µg / liter and were obtained from the filtration of 2 liters.

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zr	Zn
filter 0.45µm / 73236	< 2.5	< 0.5	< 0.5	< 0.5	< 0.5	< 1.5	< 25	< 0.5
filter SA2 / 73237	< 2.5	< 0.5	< 0.5	< 0.5	0.8	2	< 25	2.3
filter SB2 / 73238	< 2.5	< 0.5	0.5	< 0.5	< 0.5	< 1.5	< 25	< 0.5

Detection limits (given in µg / filter)

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zr	Zn
Detection limits	5	1	1	1	1	3	50	1

After 33 EFPD in test 1999/01

Table 4-11
Analysis of the primary fluid through filtrations Quantitative analysis on filters 0,45µm/SA2/SB2 by X-ray fluorescence spectrometry. The results are given in µg / liter.

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zr	Zn
filter 0.45µm / 73246	< 1.7	< 0.3	< 0.3	< 0.3	< 0.3	< 1	< 17	< 0.3
filter SA2 / 73247	< 1.7	< 0.3	< 0.3	< 0.3	< 0.3	< 1	< 17	< 0.3
filter SB2 / 73248	< 1.7	< 0.3	< 0.3	< 0.3	< 0.3	< 1	< 17	< 0.3

After shutdown (35 EFPD) in test 1999/01

Table 4-12
Analysis of the primary fluid at 60°C through filtrations Quantitative analysis on filters 0,45µm/SA2/SB2 by X-ray fluorescence spectrometry. The results are given in µg / liter.

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zr	Zn
filter 0.45µm / 73251	80	6.2	8	< 0.5	0.8	< 1.5	< 25	< 0.5
filter SA2 / 73252	130	33	< 0.5	8	33	< 1.5	< 25	< 0.5
filter SB2 / 73253	< 2.5	< 0.5	< 0.5	< 0.5	< 0.5	< 1.5	< 25	< 0.5

Detection limits in µg / filter

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zr	Zn
Detection limits	5	1	1	1	1	3	50	1

A mass balance performed at the end of the test 1999/01 gave 7.5 mg of corrosion products in the primary fluid (in soluble and particle states) and 12 mg of residual deposit on the 4 fuel claddings. This represents an average "crud" thickness of ~ 1 mg/dm^2 obtained before the shutdown, at 35 EFPD.

4.2.4 Discussion

Test 1999/01 with the highest T/H duty and steaming rate was viewed as the last resort for obtaining adequately thick crud deposits in Cirene loop *without external ion injection*. Since the crud deposits were indeed still thin in this test, it became clear that external ion injection would have to be initiated. Accordingly, the 2000 series tests, described in the next chapter, were conducted with the external ion injection.

5
2000 SERIES OF TESTS

5.1 Test 2000/01

5.1.1 Purpose and Procedure

The 2000/01 was the first test undertaken with an external injection of corrosion precursors (Fe and Ni). The purpose of *controlled* release/injection experiments is to produce a *representative* coolant source to measure experimentally the appropriate rate of deposition under realistic sub-cooled steaming conditions. This is the first step in integrating a deposition model-- yet to be developed-- into a T/H model expected to represent the AOA phenomenon fully and realistically. While this remains the ultimate goal of the Cirene tests, in practical terms, the purpose of 2000 series of tests was to create conditions in the loop that would:

(a) reproduce concentrations levels of metallic elements (Fe and Ni) that are typically similar to those in the primary circuit of the PWR

(b) achieve formation of thicker deposits onto the test rods in reasonable time-scales (1 to 2 month duration tests)

These conditions were not achievable in the tests completed in 1998 and 1999, all conducted without external injection, even with the highest thermal-duty (e.g., test 1999/01). External injection was, therefore, implemented starting with test 2000/01.

The main concern with external injection has been the controllability of Ni and Fe levels in the *heated test section*. The injection device, described in chapter 2, can only control the amounts and rates of Fe and Ni fed into the loop. The soluble and particulate concentrations within the loop will depend on the difference between the source term (ion injection and release rate of the loop) and the deposition rate on the walls of the loop. These, in turn, will depend on the chemical and thermal hydraulic conditions of the loop. Although it is possible that particulates might precipitate in the hot zones, as such, the local concentrations in the heated section will have to be estimated rather than *measured*. It is not possible to implement *in-situ* feedback system to *on-line* measure and control the concentration levels of the corrosion products in the test section. In this context, the following limitations of the Cirene facility are noteworthy:

- It is difficult to perform coolant concentration measurements more than once a week. A minimum volume of 5 liters per sample is needed due to low concentration of Ni and Fe, which *in itself* has a significant impact on the concentration of the species, given the loop volume of only 25 liters.

- Fe and Ni feed and bleed to the loop is difficult to implement. The flow rate in the test section of the Cirene loop is 5 tons per hour. A total feed and bleed system for a one month run will need 3500 tons of water with the right concentration of Ni and Fe and heated at 284 °C. It is impractical to have such a large coolant throughput in the Cirene loop.

The reference test for 2000/01 regarding T/H parameters was 1998/01, corresponding to a low level of sub-nucleate boiling regime in the test section. The chemical conditions, set to 1.4 ppm lithium and to 1000 ppm boron, corresponded to a pH level of 6.9 at 305°C. A rapid shutdown, without oxygenation was scheduled after ~ 20 EFPD with continuous injection of corrosion precursors. The purpose was to preserve the crud deposits on the test rods. Table 5-1 shows a comparison between the two tests.

Table 5-1
Thermal-hydraulic and chemical conditions selected for the 2000/01 Test – Compared to the 1998/01Test

PARAMETERS	1998/01 TEST	2000/01 TEST
Pressure (bar)	150	150
Inlet mass flow rate (g/cm² s)	250	250
Test section inlet temperature (°C)	311	310
Test section outlet temperature (°C)	337	337
Max. cladding wall temperature (°C)	344.5	344.6
Heat flux (W/cm²)	70.5	70
Outlet evaporation rate (kg/m^2.hr)*	1 880	1 800
[B] ppm	2 000	1 000
[Li] ppm	2	1.45
pH (300°C)	6.7	6.9
[H_2] ppb	25 - 50	30 - 40
[O_2] ppb	< 10	< 10
CVCS. flow rate (l/hr)	-	~ 4 (without clean-up)

* in the average sub-channel of the test-section

By applying an average mass flow of 250 g/cm^2.s and a constant heat flux of 70 W/cm^2 on each cladding rod, a global evaporation rate of 1 800 kg/m^2.hr (0.05 g/cm^2.s) is obtained in the outlet average sub-channel of the test section, with an inlet temperature of 310°C. The cladding wall temperature reaches a maximum temperature of 344.6 °C at 77 cm axial elevation as shown on Figure 5-1.

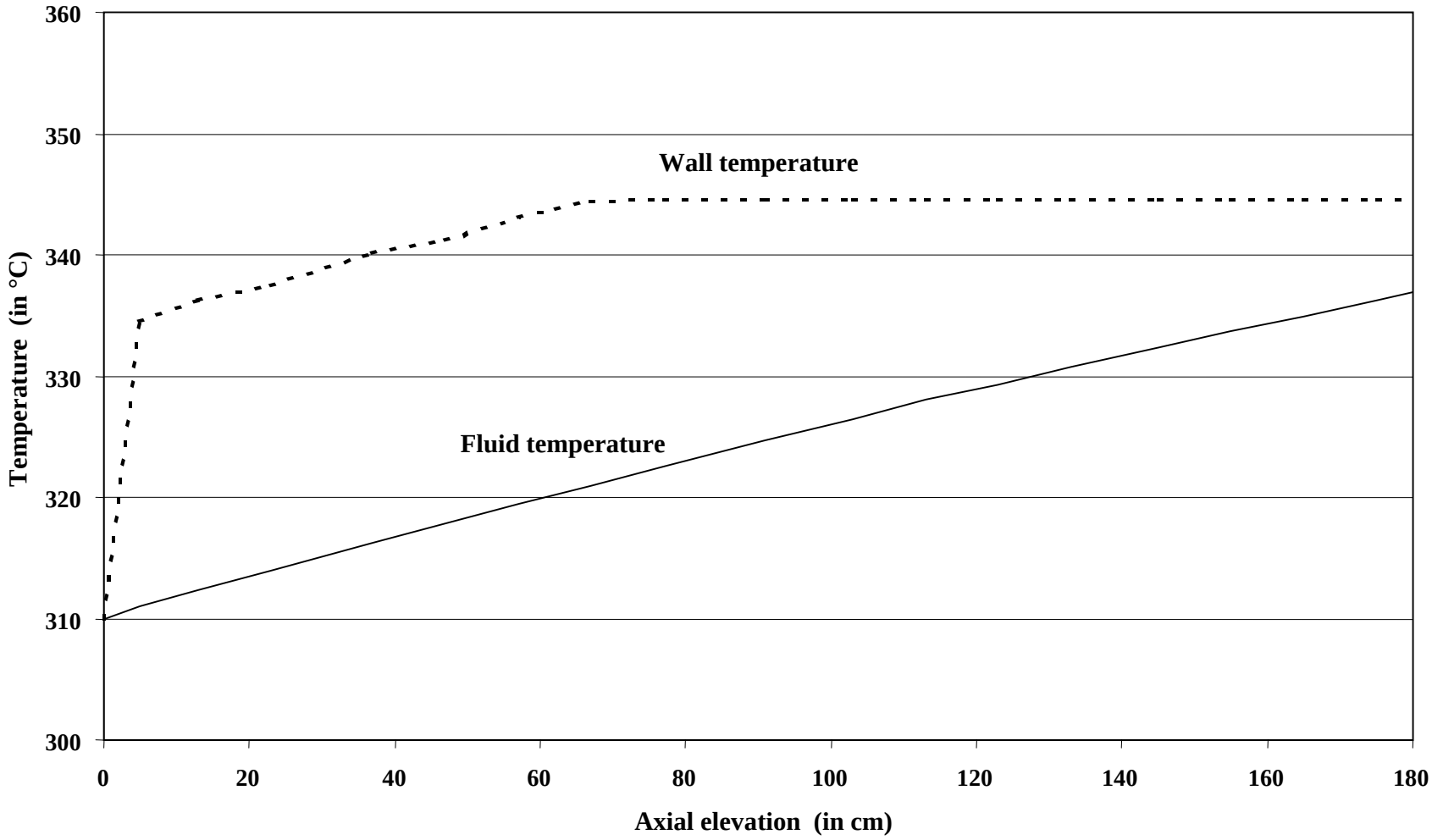


Figure 5-1
Fluid temperature and cladding wall temperature in the average sub-channel in test 2000/01 (FLICA 4 calculations)

Additional FLICA calculations are for test 2000/01 are given in Appendix B

5.1.2 Test Operation and Ion Injection

For this test, the CVCS flow rate has to be set to 4 l/hr without circulation to the anion- and cation-exchanger resins (unless an adjustment for primary fluid levels of boron and lithium was required). During the test, oxygen and hydrogen concentrations in the primary fluid were monitored from the CVCS, as well as the pH number and the electrochemical potential.

The injection of Fe and Ni was started after a few operating days with the required thermal-hydraulic and chemical conditioning. The quantity of material released by the constituent materials of the primary circuit - i.e. 0.95 m² of Inconel 600 and 1.65 m² of stainless steel 316 - will be supplemented by the quantity of material injected into the primary fluid. The objective was to inject, during the planned 20 days test duration, around 190 mg of nickel and around 50 mg of iron with injected rates of respectively 0.4 and 0.1 mg/hr. The specific setting for the ion injection device is given hereafter in the Table 5-2.

Table 5-2
2000/01 Cirene Test - Specific setting for the ion injection device

	Iron vessel	Nickel vessel
[B] , [Li] , $pH_{25°C}$	1 000 ppm / 1.4 ppm; pH ~ 6.6	1 000 ppm / 1.4 ppm; pH ~ 6.6
Concentration in soluble state	C_{Fe} (in g/l)	C_{Ni} (in g/l)
Flow rate of the injection pumps	D_{Fe} (in ml/hr) = 0.1 / C_{Fe}	D_{Ni} (in ml/hr) = 0.4 / C_{Ni} Ni / Fe ~ 4
Controlled leak-off on the primary circuit : $D_{RCP} = (D_{Fe} + D_{Ni}) \times 0.024$ in liters/day		
Total injected mass	~ 240 mg after ~ 20 days with injection	
Expected « CRUD » thickness (material release and injection)	if deposited - only on the fuel rods : ~ 12 mg/dm² - on all the RCS : ~ 1 mg/dm²	

The 2000/01 test stopped with a rapid unscheduled shutdown after 28 EFPD of operations, of which 22 EFPD involved Fe and Ni injection. The shutdown was caused by a malfunction of the CVCS pump that led to pressurizer level below lower threshold. Thus after an effectively 17 EFPD of Fe injection and 13 EFPD of Ni injection, and 6 EFPD at 282°C without injection, the test concluded without oxygenation. The primary fluid cooling rate was about 30°C/hour. Primary fluid samples was also collected at 60°C for chemical analysis.

The total amount of Fe injected was ~ 62 mg during 402 hours (17 EFPD), which corresponds to an injection rate of 0.15 mg/hr. The total amount of Ni injected was ~ 112 mg during 112 hours (13 EFPD), which corresponds to an injection rate of 0.37 mg/hr. The injection rate ratio actually proved to be close to 2.5, compared to the planned value of the ratio between 3 and 4. This was because of some minor initial problems with injection device that have since been solved. The injected mass ratio of Ni/Fe was 1.8.

5.1.3 Results

Visual Inspection

The original metallic brightness of the Zry 4 claddings was no longer visible, and a homogeneous gray stain was detected all along the claddings. No specific coloring related to crud deposition was seen. Likewise, the unheated portions of Zry surfaces (below and above the heated section) indicated no specific coloring related to crud coverage.

Coolant Analysis

Table 5-3 shows the results of a chemical impurity analyses of the primary fluid and compares it with the specified values. The data indicate no abnormality.

Table 5-3
Impurity contents of the primary fluid at 4 EFPD (results are given in mg / l)

Elements	SO_4	Cl	F	Al	Ca	Si	Mg	Na	K
Specification	< 0.15	< 0.15	< 0.15	< 0.05	< 0.05	< 1	<0.05	< 0.2	-
Measurement (4301/02)	< 0.08	0.35	< 0.05	0.08	0.55	0.18	-	-	0.27

Filtration analysis (0.45µm/SA2/SB2) of the primary fluid at 15 EFPD (after 9 EFPD of Fe and Ni injection) is shown in Table 5-4. The data indicate two times more nickel (6.2 µg/l) than iron (2.7 µg/l) in the primary fluid, in soluble state. The equivalent values in the tests without Fe, Ni injection (the 1998 and 1999 series) were Ni_{sol} < 0.35 µg/l and Fe_{sol} < 1.7 µg/l. At this stage of test 2000/01, Fe and Ni had been injected with a Ni/Fe ratio of 2.5. (12-14 mg of Fe injected / 32-34 mg of Ni injected).

Table 5-4
Analysis of the primary fluid trough filtrations (0.45µm/SA2/SB2) at 15 EFPD_After 9 EFPD of Fe and Ni injection (12-14 mg of Fe injected / 32-34 mg of Ni injected) (The results are given in µg / liter)

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zn	Zr
Filter 0.45µm / 4331	< 2.5	410	< 0.5	< 0.5	2.8	< 1.5	1.25	< 25
filter SA2 / 4332	2.7	6.2	< 0.5	1	3.2	1.7	2.4	< 25
filter SB2 / 4333	< 2.5	< 0.5	< 0.5	< 0.5	3	< 1.5	1.3	< 25

Table 5-5 shows the same data as in Table 5-4 at 26 EFPD (after 20 EFPD of Fe and Ni injection). At this stage of the test, the Fe and Ni concentrations were, respectively < 2.5 µg/l and 0.9 µg/l in particulate state, and 5.8 µg/l and 1.6 µg/l in soluble state. These results fit well with typical values in PWR, and point out that the injection device is well adapted.

Table 5-5
Analysis of the primary fluid by filtrations (0.45µm/SA2/SB2) at 26 EFPD After 20 EFPD of Fe and Ni injection (53-55 mg of Fe injected / 83-85 mg of Ni injected) (the results are given in µg / liter)

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zn	Zr
Filter 0.45µm / 4331	< 2.5	0.9	0.7	< 0.4	<0.2	< 0.6	< 0.2	< 10
filter SA2 / 4332	5.8	1.6	0.7	< 0.4	<0.2	7	0.4	< 10
filter SB2 / 4333	< 2.5	< 0.5	0.8	< 0.4	< 0.2	< 0.6	< 0.2	< 10

The concentration levels obtained for all the metallic elements, at 26 EFPD, are reported in Figure 5-2.

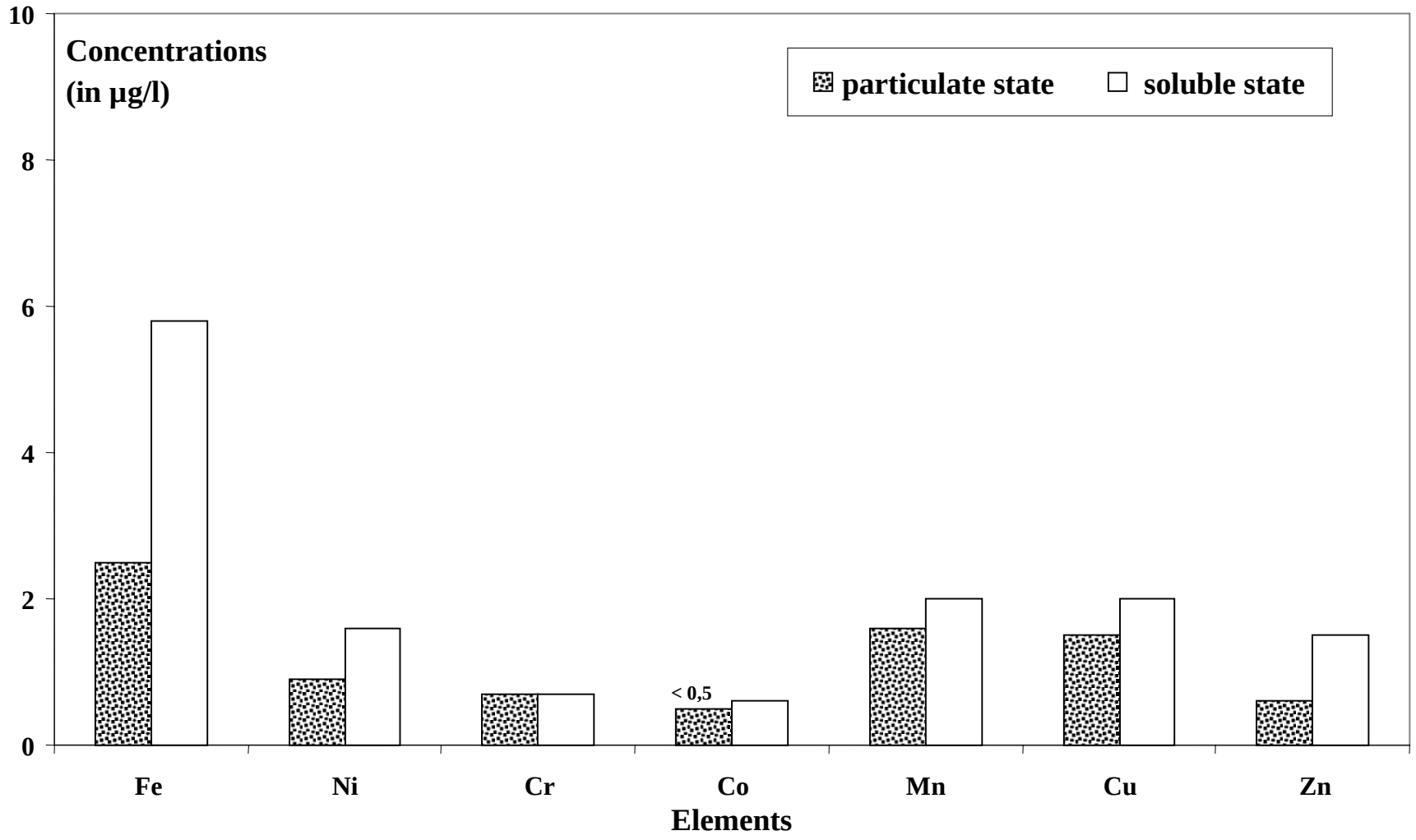


Figure 5-2
Metallic Concentrations in the Primary Fluid at 26 EFPD (after the injection of 54 mg of Fe, and 85 mg of Ni)

Filtration analysis (0.45µm/SA2/SB2) of the primary fluid at 282 °C, after 28 EFPD at 310°C + 3 EFPD at 282°C (with 22 EFPD of Fe and Ni injection: 61 - 63 mg of Fe injected / 110 - 112 mg of Ni injected), is shown in Table 5-6.

Table 5-6
Analysis of the primary fluid by filtrations (0.45µm/SA2/SB2) at 282 °C After 28 EFPD at 310°C + 3 EFPD at 282°C (with 22 EFPD of injection: 61 - 63 mg of Fe injected / 110 - 112 mg of Ni injected). (the results are given in µg / liter)

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zn	Zr
filter 0.45µm /4411	< 3.5	< 0.7	1.7	< 0.7	< 0.7	2	< 0.7	< 35
filter SA2 / 4412	9.7	0.9	0.8	1	3	2.2	0.75	< 35
filter SB2 / 4413	< 3.5	< 0.7	1.3	< 0.7	2.5	2	< 0.7	< 35

Table 5-7 shows filtration analysis (0.45µm/SA2/SB2) of the isolated test section, at 60 °C during the shutdown, after 28 EFPD at 310°C + 6 EFPD at 282°C (with 22 EFPD of Fe and Ni injection: 61 - 63 mg of Fe injected / 110 - 112 mg of Ni injected).

Table 5-7
Analysis of isolated test section, at 60 °C during the shutdown After 28 EFPD at 310°C + 6 EFPD at 282°C (with 22 EFPD of injection: 61 - 63 mg of Fe injected / 110 - 112 mg of Ni injected). (the results are given in µg / liter)

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zn	Zr
filter 0.45µm /4416	93	6.6	5.6	0.9	2.1	1.9	0.8	< 25
filter SA_2 / 4417	190	250	0.8	10.8	100	1.9	7.3	< 25
filter SB_2 / 4418	< 2.5	< 0.5	0.7	< 0.5	2	1.5	0.7	< 25

From the data given in Tables 5-7, the following can be noted:

- In the particulate state, Fe is mainly detected, with Fe_{part} = 93 µg/l, compared to Ni_{part} = 6.6 µg/l. This is equivalent to, respectively, 2.3 mg Fe_{part} and 0.16 mg Ni_{part} in the total volume (25 liters) of the system (see Figure 5-3). These are at the same levels as those obtained during the shutdown of test 1999/01 (see chapter 4).
- In the soluble state, Ni and Fe are mainly measured, with Ni_{sol} = 250 µg/l and Fe_{sol} = 190 µg/l. This is equivalent to, respectively, 6.25 mg Ni_{sol} and 4.8 mg Fe_{sol} present in the 25

liters of the RCS (see Figure 5-3). These concentrations in soluble states, at the stage of the shutdown, correspond to a Ni/Fe_{sol} ratio of 1.3, which is greater than the Ni/Fe_{sol} ratio of the 1999/01 Cirene test without injection, where this ratio was $Ni/Fe_{sol} = 0.25$.

Crud Analysis

Chemical analysis (by X-ray fluorescent spectrometry) of the crud scraped from Cladding No 4 after the test is given in Table 5-8.

Table 5-8
The results of semi-quantitative analysis of crud scrapes from Cladding No 4 in test 2000/01 (Data given in µg / filter)

Axial elevation	15 cm	60 cm	110 cm	160 cm
Analysis No.	44694	44693	44692	44691
Fe	18	6.2	15.7	44.4
Ni	5.6	4	3.3	12.2
Cr	5.6	5.5	5.3	4.7
Co	2.5	2	2	2.6
Mn	5.8	6.2	6.2	6.3
Cu	6.7	8	7	4.4
Zn	4	3	4	6.5
Zr	230	257	230	83

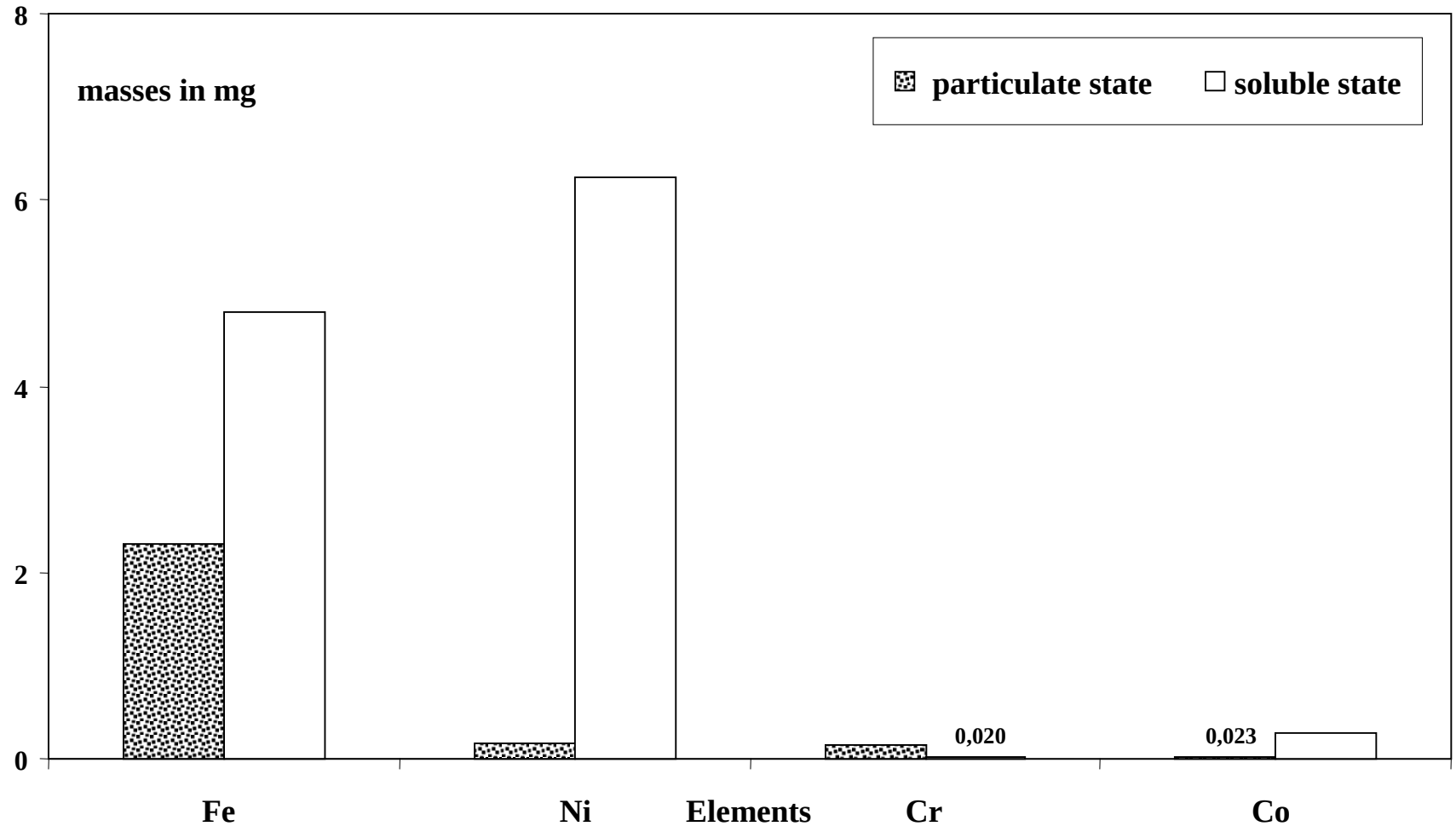


Figure 5-3
Global Composition of Metallic Elements in the Primary Fluid (25 l) during the Shutdown

The data in Table 5-8 show a high contribution of the Zr (from 50% to 85 % of the total signal), except in the upper most section. Radiochemical analysis of Cladding No 4, before and after crud scraping is summarized in Tables 5-9 a and b. The radioactivity levels are rather weak, even before crud scraping. The activity data also indicate that some incorporation of ^{60}Co may have occurred in the Zry oxide.

Table 5-9a
Radioactivity measured on Cladding No. 4 before crud scraping (Thermal-hydraulic data related to the average sub-channel appended for reference)

Axial elevation	15 cm	60 cm	110 cm	160 cm
^{58}Co	N.D	N.D	N.D	N.D N.D on 4 claddings
^{54}Mn	N.D	N.D	N.D	N.D 0.62 on 4 claddings
^{60}Co	0,9	0,97	0,96	1.23 16.2 on 4 claddings
Wall temp.	336.4°C	343.8°C	344.5°C	344.5°C
Liq. temp.	312.4°C	319.9°C	328°C	334.2°C
Global Gvap	0	0	721 kg/m^2.hr	1 460 kg/m^2.hr
Global Gvap	0	0	0.02 g/cm^2.s	0.04 g/cm^2.s

Table 5-9b
Radioactivity measured on cladding No. 4 after CRUD scrapings

Axial elevation	15 cm	60 cm	110 cm	160 cm
^{58}Co	N.D.	N.D.	N.D.	N.D.
^{54}Mn	N.D.	N.D.	N.D.	N.D.
^{60}Co	0.89	0.93	0.89	1.14

Arbitrary unit (100 . Gamma / cm² s)
Activity values given with 15 % uncertainty on one cladding, and 10% on all four claddings
N.D: non-detected element
Measured distances in relation to 5.8-cm diode.

5.1.4 Discussion

Residual Crud Density

The residual crud density on the Cladding No 4 obtained by weighing the crud scrapes, is presented in Table 5-10. The results have a ± 15% uncertainty.

Table 5-10
Residual surface crud densities (after shutdown at 34 EFPD) and the estimated global steaming rate in the average sub-channel

axial elevation	15 cm	60 cm	110 cm	160 cm
Estimated surface density	~ 0.13 mg/dm²	~ 0.17 mg/dm²	~ 0.08 mg/dm²	~ 0.42 mg/dm²
Global Gvap	0	0	721 kg/m^2.hr	1 460 kg/m^2.hr

The data are also represented graphically in Figure 5-4. The residual crud surface density of 0.42 ± 0.06 mg/dm^2 in the upper section of the Cladding No 4 is four times greater than the lower part under T/H single-phase conditions.

Crud Composition

The relative chemical composition of the crud scraped at 160-cm axial level is given in Table 5-11. The % values are from X-ray fluorescent spectrometry results, excluding Zn and Zr.

Table 5-11
Relative chemical composition of the crud at the 160-cm axial elevation on Cladding No 4

Element	Fe	Ni	Cr	Co	Mn	Cu
%	59 %	16 %	6 %	3.5 %	8 %	6 %

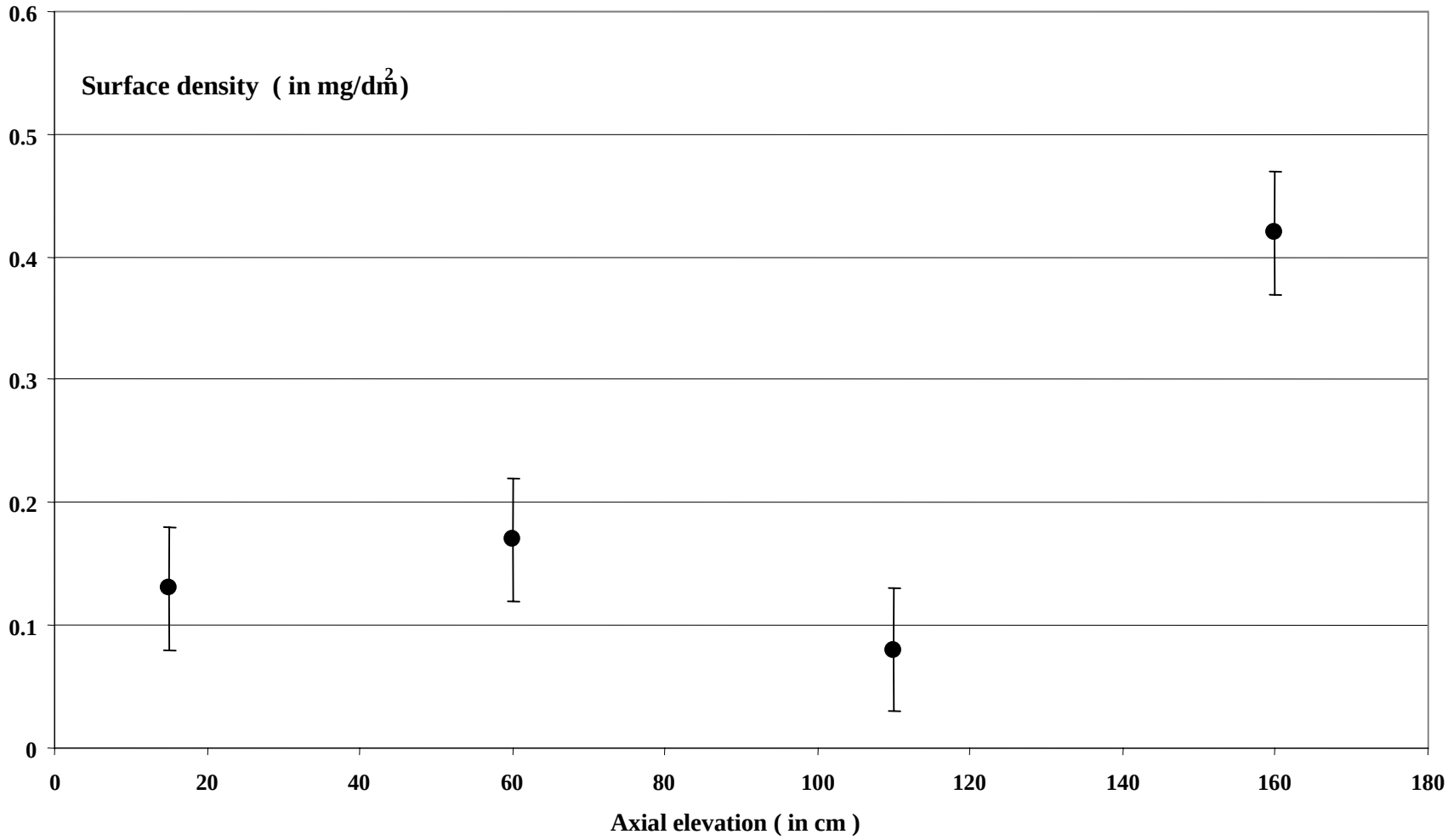


Figure 5-4
Surface Density of the Residual Crud on the Cladding No 4

The Ni/Fe ratio of the residual crud is ~ close to 0.30. It is evaluated at only one axial elevation (scraping with the low Zr signal), taking into account the chemical results of the X-ray fluorescent spectrometry. Assuming that most of the matter of Ni and Fe presents in the primary fluid, at the shutdown, comes from the dissolution of the crud formed on the 4 fuel claddings, the total quantity of Ni in the primary fluid, in soluble and particulate states – 6.5 mg - is added to the total quantity of Ni presents on the 4 heating length claddings – 0.54 mg. The same calculation is made for the iron, with respectively 7.1 mg and 1.7 mg. The average Ni/Fe ratio of the *as-deposited* crud is given by (6.5 + 0.54 = 7.04 mg) / (7.1 + 1.7 = 8.8 mg) = 0.8

It is obvious that there is a deficiency of nickel in the crud Ni/Fe ratios in test 2000/01. The estimated ratios for residual as well as as-deposited crud are lower than corresponding ones in the PWR, and even from previous tests from 1998 and 1999. Presently, one can only speculate of an interaction between the nickel and the primary circuit materials. Such interaction has been observed previously for the carbon steel surfaces.

Mass Balance

The amounts injected (i.e., 62 mg of Fe and 112 mg Ni) and the material released from the system (i.e. ~ 75 mg of Fe and ~ 130 mg of Ni) during this test, provide the following estimates of expected crud deposition:

- a value of 19.2 mg/dm^2, if deposited uniformly but only on the 4 fuel claddings (area of 19.75 dm^2)
- a value of 1.12 mg/dm^2, if deposited uniformly on all the primary circuit surfaces (area of 337 dm^2)

These estimates are for as-deposited values (i.e., *before shutdown*). The coolant analysis data during the shutdown of test 2000/01 indicate ~ 17 mg of corrosion products in primary fluid:

(a) ~ 2.8 mg in particulates (2.3 mg Fe)

(b) ~ 14 mg in soluble state (6.25 mg Ni and 4.8 mg Fe)

If the released material during shutdown came essentially from the heated rods and adding ~ 4 mg of residual deposit (Table 5-10), the total as-deposited crud mass was 20.8 mg. If deposited uniformly over all heated rod surface area, this results in crud coverage of 1.1 mg/dm^2. In addition, the crud surface density on the shroud around the rod bundle was close to 0.95 mg/dm^2. These numbers indicate a uniform deposition on all surface area.

Although the reasoning above seems to indirectly satisfy the mass balance, the concern were raised whether (Fe+Ni) was being deposited *preferentially* somewhere else in the loop. For example, there could be material traps in the system (such as the knit meshes) or sinks (piping elbows, etc.) Except for the shroud around the heated section and the unheated portions of the rod bundle, it was not possible to visually inspect or gamma scan the reminder of primary circuit surfaces to alleviate this concern.

5.2 Test 2000/02

5.2.1 Purpose and Procedure

The lack of crud even with external injection was a concern. Although the preceding test had ion injection, it was not conducted at the highest T/H duty possible. Therefore, it was decided to increase the T/H duty in test 2000/02 to be at the same level as in test 1999/01 (see chapter 4). In addition, the injection rate was doubled compared to test 2000/01 to increase the probability of adequate crud deposition. In other words:

- Double the injection rates for Ni and Fe compared to test 2000/01
- Apply the same T/H conditions as in test 99/01
- Maintain Li/B chemistry and pH the same as in test 2000/01

Minimum test duration of 22 EFPD was foreseen. With these T/H parameters, according to the FLICA 4 calculations, the maximum wall temperature equals ~ 341°C, and the steaming rate reaches ~ 2 530 kg/m^2.hr at the exit of the test section, in the hot sub-channel (see Table 5-12).

Table 5-12
Specified parameters for test 2000/02

PARAMETERS	2000/02 CIRENE TEST
Pressure (bar)	143
Inlet mass flow rate (g/cm² s)	230
Test section inlet temperature (°C)	307
Test section outlet temperature (°C)	337.5
Max. cladding wall temperature (°C)	340.9
Heat flux (W/cm²)	75
Outlet evaporation rate (kg/m^2.hr)*	2 560
[B] ppm / [Li] ppm	1 000 / 1.45
pH (300°C)	6.9
[H_2] ppb	30 - 40
[O_2] ppb	< 10
C.V.C.S. flow rate (l/hr)	~ 4 (without clean-up)
Ni : Fe injection rate	0.8 mg/hr : 0.2 mg/hr

The objective was to inject continuously, during ~ 20 days, at an injected rate of ~ 0.8 mg/hr for the nickel, and ~ 0.2 mg/hr for the iron. The specific settings for the ion injection device, for this 2000/02 Cirene test, are given hereafter in the Table 5-13.

Table 5-13
2000/02 Cirene Test: specific settings for the ion injection device

	Iron vessel	Nickel vessel
Concentration in soluble state	C_{Fe} (in g/l)	C_{Ni} (in g/l)
Flow rate of the injection pumps	D_{Fe} (in ml/hr) = 0.2 / C_{Fe}	D_{Ni} (in ml/hr) = 0.8 / C_{Ni} Ni / Fe ~ 4
Controlled leak off on the primary circuit : $L_{RCS} = (D_{Fe} + D_{Ni}) \times 0.024$ in liters / day		
Total injected mass	~ 480 mg after ~ 20 days with injection	
Expected « CRUD » thickness	if deposited - only on the 4 fuel rods : ~ 24 mg/dm^2 - on all the RCS : ~ 1.4 mg/dm^2	

5.2.2 Operation

Test 2000/02 started on 20th July 2000, with the Fe and Ni injections initiating on 27th July 2000. On 30 July 2000, an unscheduled shutdown of the loops occurred because of an incident on the main power transformer. The problem was rectified and test restarted on 1st Aug. 2000.

After the equivalent of ~ 6 days of injection, ~ 42 mg of Fe (0.3 mg/hr for ~ 5.75 EFPD) and ~ 143.3 mg of Ni (1.15 mg/hr for ~ 5.2 EFPD) had been injected. The actual Fe and Ni rates are higher than the target values (0.2 and 0.8 mg/hr), with an Ni/Fe injected ratio closed to 3.4. The test stopped with another unscheduled shutdown after 16 EFPD, with 9 EFPD of Ni and Fe injections due to leaks on the heat-exchanger. At this stage:

~ 58 mg of Fe had been injected, with an injection rate of ~ 0.28 mg/hr (actual injection of 8.5 EFPD)

~ 210 mg of Ni had been injected, with an injection rate of ~ 1 mg/hr (actual injection of 8 EFPD)

The Ni/Fe injection ratio had reached the value of 3.6

5.2.3 Results

Visual Inspection

Visual inspection of the heated rods after 16 EFPD showed no specific coloring related to crud coverage.

Coolant Analysis

Table 5-14 and 5-15 show, respectively, the coolant analysis at 5 EFPD and 12.5 EFPD. It should be noted that the data at 5 EFPD were taken even before the Fe and Ni injections.

Table 5-14
Analysis of the primary fluid through filtrations (0.45 µm/SA2/SB2) at 5 EFPD, before the Fe and Ni injections. The results are given in µg / l

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zn
Part. 0.45µm / 73188	< 2.5	8	< 0.5	< 0.5	2.9	1.8	1
Soluble / 73189	12	6	0.6	0.8	4.2	3	4
Soluble / 73190	< 2.5	< 0.5	< 0.5	< 0.5	3	1.9	1

Table 5-15
Analysis of the primary fluid through filtrations (0.45 µm/SA2/SB2) at 12.5 EFPD, after 6 EFPD with Fe and Ni injection (42 mg of Fe injected / 143 mg of Ni injected). The results are given in µg / l.

Elements	Fe	Ni	Cr	Co	Mn	Cu	Zn
Part. 0.45µm / 4441	< 2.5	7	< 0.5	< 0.5	1.9	< 1.5	< 0.5
Soluble / 4442	3	25	< 0.5	< 0.5	3.3	< 1.5	2.8
Soluble / 4443	< 2.5	< 0.5	< 0.5	< 0.5	2	< 1.5	< 0.5

5.2.4 Discussion

The Fe and Ni concentrations obtained during operation, in the primary fluid, fit well with the expected Fe, Ni concentration levels, *before the injection*, as can be seen in Table 5-14. In addition, the visual examination at 16 EFPD indicated no preferential crud formation in the upper part of the claddings. This observation is similar to that in test 2000/01, also undertaken with an external injection of Fe and Ni albeit at a lower T/H duty. Although a suitable level of corrosion products was achieved in the primary fluid in both these tests, low crud coverage and an effectively uniform deposition on all primary surfaces was observed. Therefore, it was decided to check the loop calibration to verify the imposed T/H conditions.

5.3 Cirene Loop Calibration

A thermal balance of the loop was evaluated at 282°C. The ratio {measured power/applied power} gave a deviation around ± 10 %, compared to the expected value deviation around ± 3 - 4 %. This exercise indicated that one, or more T/H parameter did not correspond to the set value. Subsequently, the following measuring devices were re-calibration of in the Cirene loop:

- Inlet temperature of the test section
- Outlet temperature of the test section
- Heat flux applied to each heating rod
- Outlet temperature of the heat exchanger

The results of the calibration tests are presented in Table 5-16 for the set points of test 2000/02.

Table 5-16
Comparison between the set points of the 2000/02 test and the actual experimental values

PARAMETERS	2000/02 set points	Actual values
Pressure (bar)	143	143
Heat flux (W/cm²)	75	75
Test section inlet temperature (°C)	307	304 (- 3 °C)
Test section outlet temperature (°C)	337.5	333.8 (- 3.7 °C)
Inlet mass flow rate (g/cm² s)	230	246.3 (+ 8%)
Outlet evaporation rate (kg/m².hr)*	2 400 *	2 000 *

***** given by FLICA 4 calculations in the average sub-channel

According to the FLICA 4 calculations with "Actual Values", the actual steaming rate in test 2000/02 reached only 2 000 kg/m^2.hr at the exit of the test section, compared to the required value of 2 400 kg/m^2.hr. Figures 5-5 and 5-6 show the axial evolution of the Global Evaporation rate (Gvap) and Liquid Temperature (Liq. T.) in the Cirene test section.

The results of these calibration tests have demonstrated the necessity of reconsidering the T/H set points. It should be noted that the inlet mass flow rate has not been re-calibrated at present, as it would have meant a long unavailability of the loop. The reported test parameters throughout this report have not yet been corrected. A full evaluation of loop calibration and resulting corrections of the reported values from chapters 3, 4, and 5 will be undertaken in the future.

The "Actual Values" in Table 5-16 are lower in temperature and higher in flow rate. While this will affect the steaming rate reported on previous tests, it does not affect anything else. All prior tests had equal or higher steaming rates compared to typical in-core values (as computed by codes such as VIPRE-01). The lower than set-point steaming rates in Cirene tests is still representative of local core conditions and is not expected to change the significantly current conclusions.

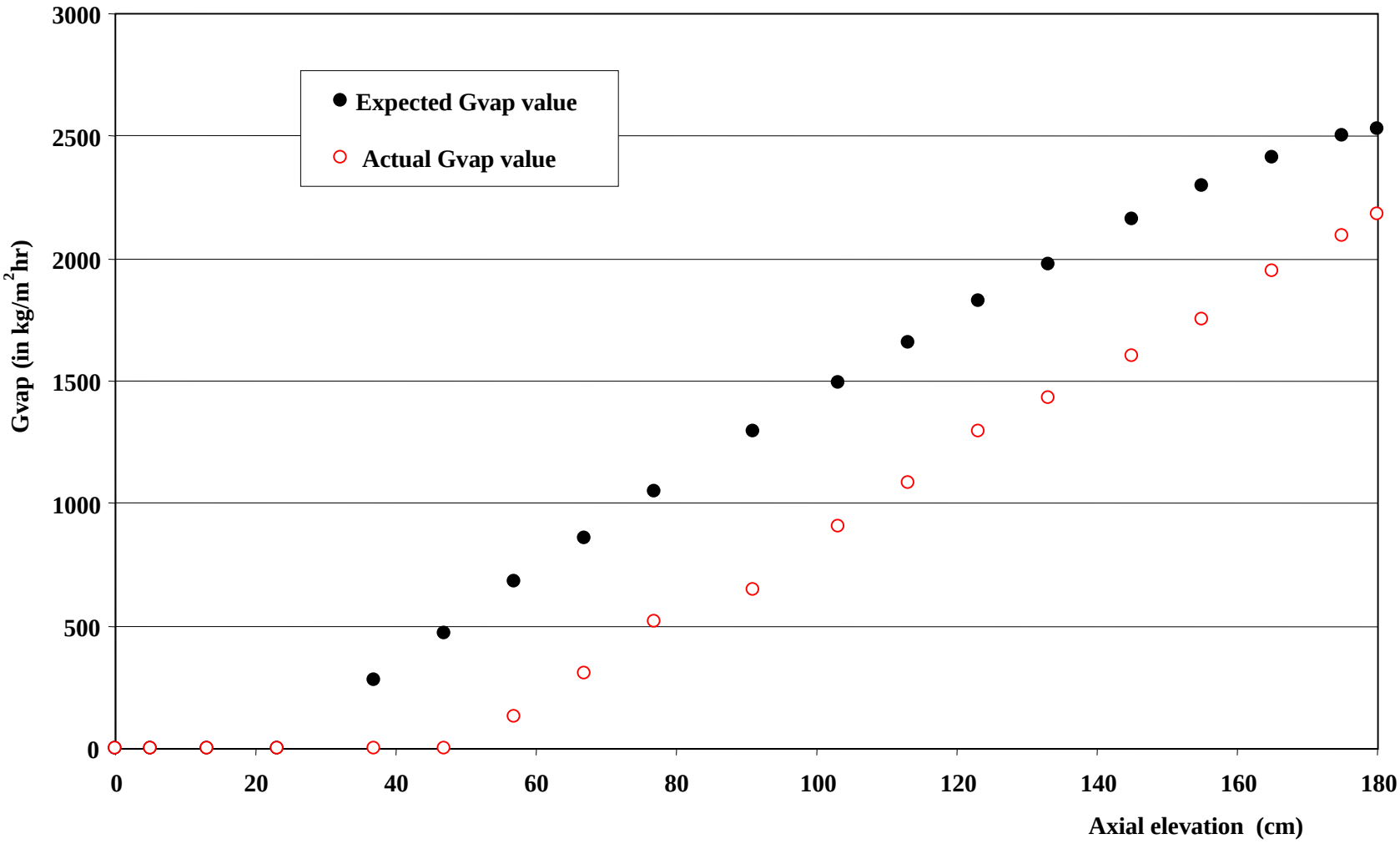


Figure 5-5
2000/02 Cirene Test - Axial evolution of Gvap in the test section based on the expected and the actual T/H values

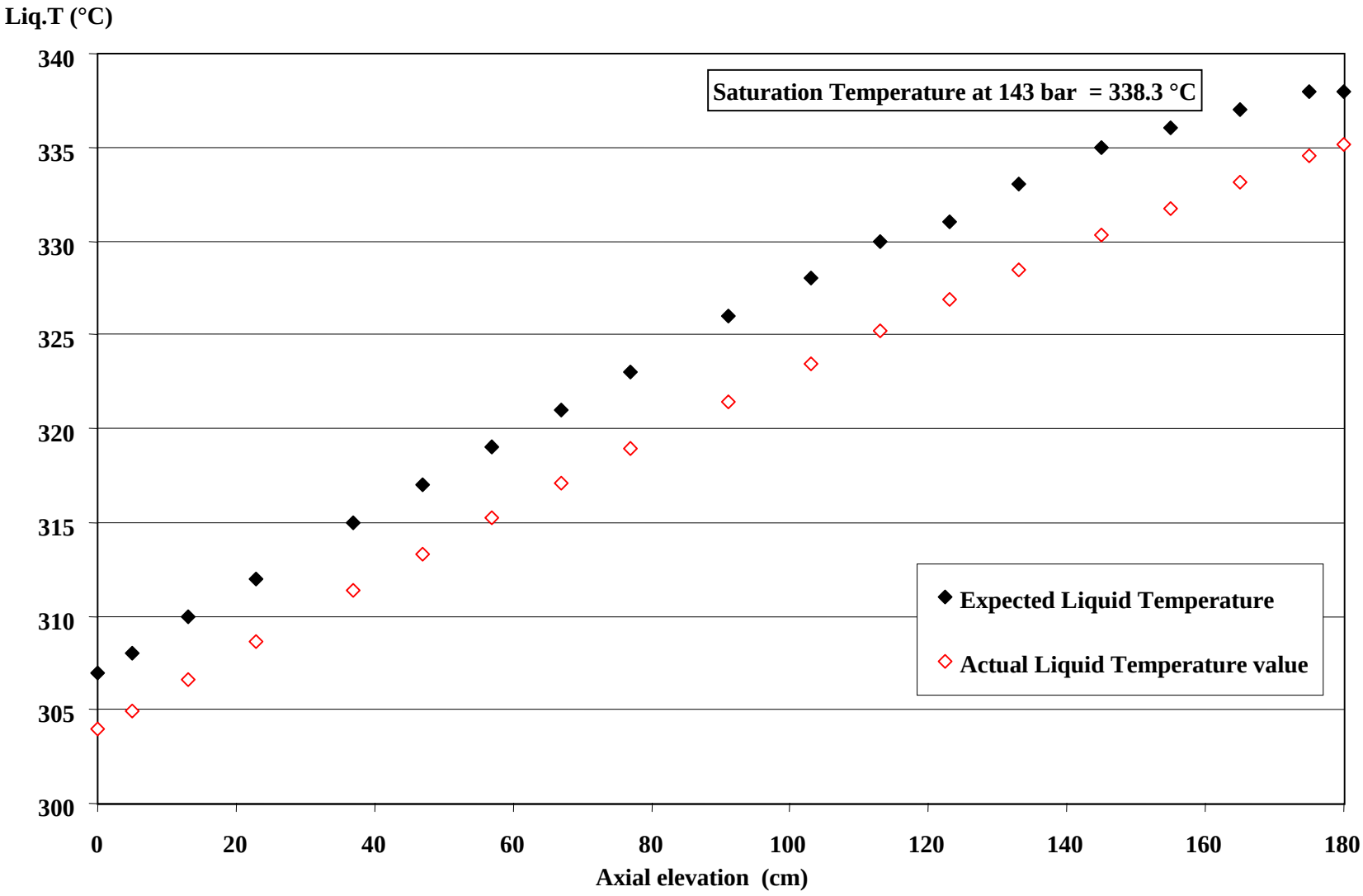


Figure 5-6
2000/02 Cirene Test -Axial evolution of Liquid T in the test section based on the expected and the actual T/H values

5.4 Test 2000/03

5.4.1 Purpose and Procedure

In order to reach the desired highest available evaporation rate at the outlet of the test section, it was clear that the heat flux applied on the rods have to be enhanced up to 83-85 W/cm^2. Thus, the nominal conditions for the next 2000/03 Cirene test were adjusted as in Table 5-17. The necessary FLICA 4 calculations were based on an actual inlet mass flow rate of 246 g/cm² s.

Table 5-17
2000/03 nominal T/H conditions

2000/03 CIRENE TEST	Expected values and FLICA 4 calculations*
Pressure (bar)	143
Inlet mass flow rate (g/cm² s)	246
Test section inlet temperature (°C)	307
Test section outlet temperature (°C)*	337.6 *
Heat flux (W/cm²)	83
Outlet evaporation rate (kg/m^2.hr) *	2 720 *

* from FLICA 4 calculations in the average sub-channel

The global outlet evaporation rate would reach a value around 2 720 kg/m^2.hr, with a test section outlet temperature around 337.6 °C, which is a value just below the theoretical saturation temperature of 338.3°C at 143 bar.

The axial evolution expected for the Liquid Temperature (Liq. T.) and for the Global Evaporation rate (Gvap) for the next 2000/03 Cirene test, are presented in Figure 5-7. These data are compared to the previous 2000/02 Cirene test. Similar calculations were performed[1] using VIPRE-01 code with no grid effects and the Chen heat transfer correlation. As can be seen in Figure 5-8 and 5-9 that the extent of steaming in test 2000/03 will be much greater than that in 2000/02.

[1] Courtesy of K. Epperson (Duke Power)

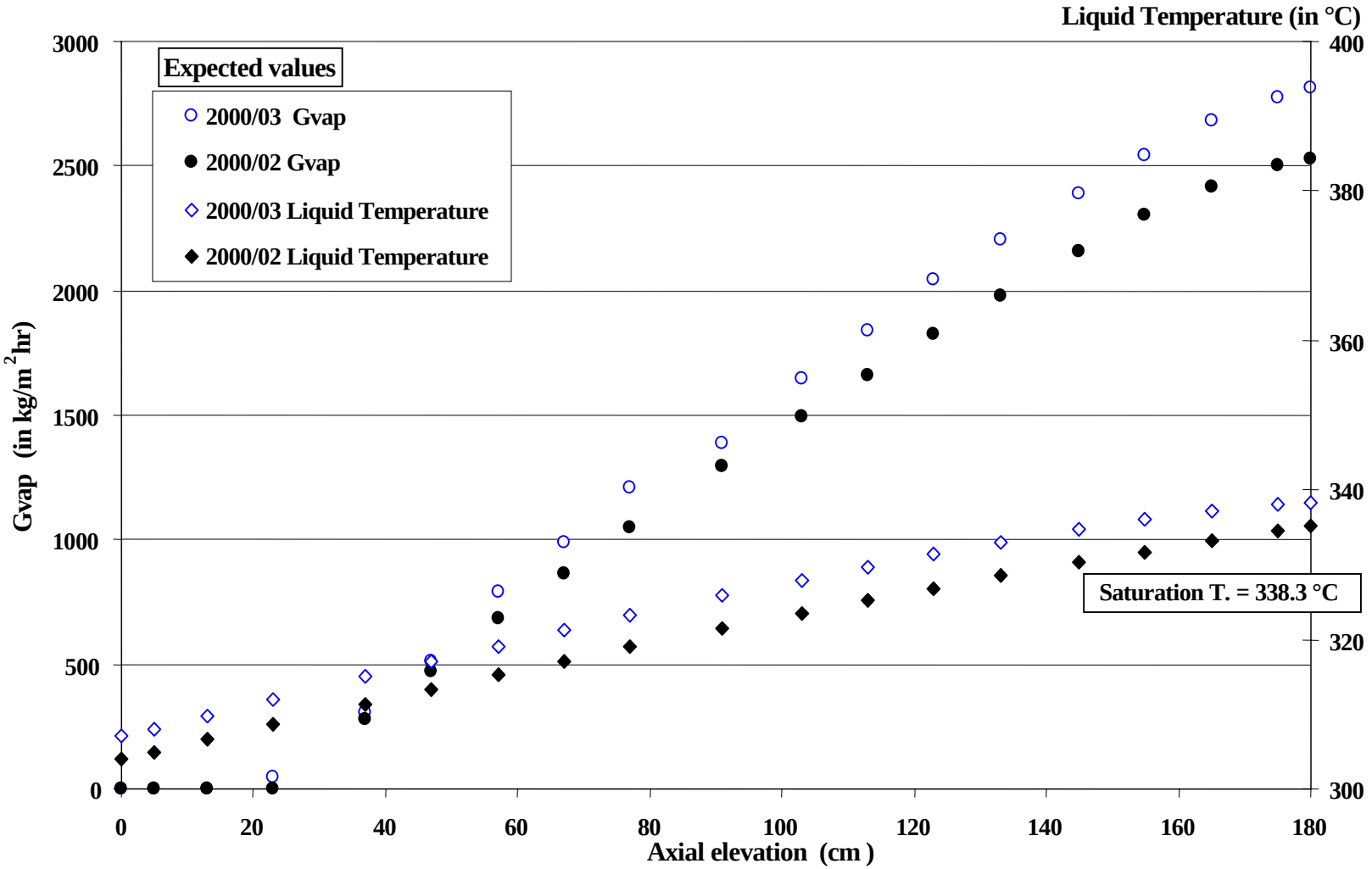


Figure 5-7
Cirene Tests 2000/02 and 2000/03 - FLICA 4 Calculations Comparison of the axial evolutions for Gvap and Liquid Temperature in the test section

2000 Series of Tests

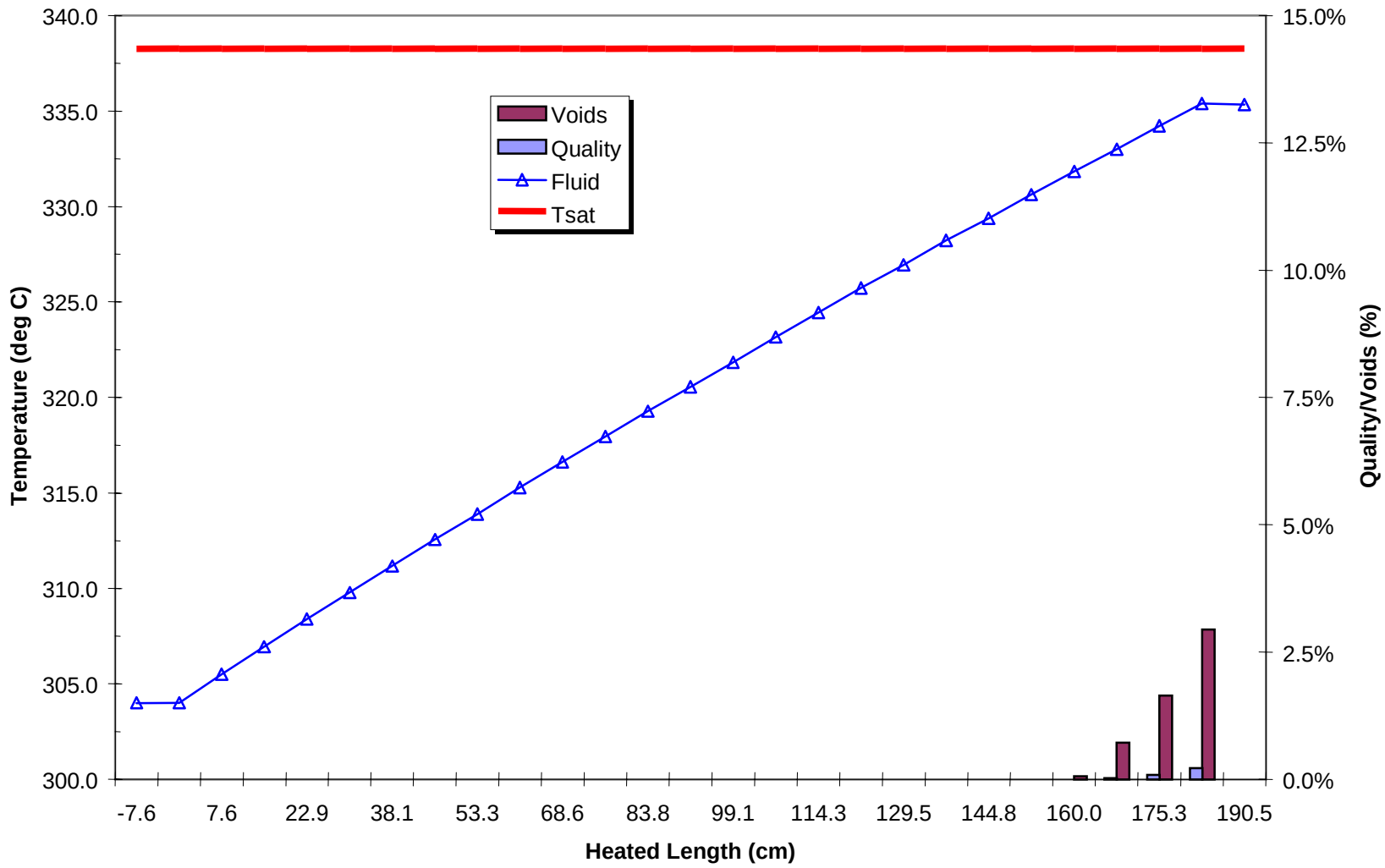


Figure 5-8
Injection Test 2000/02 Actual

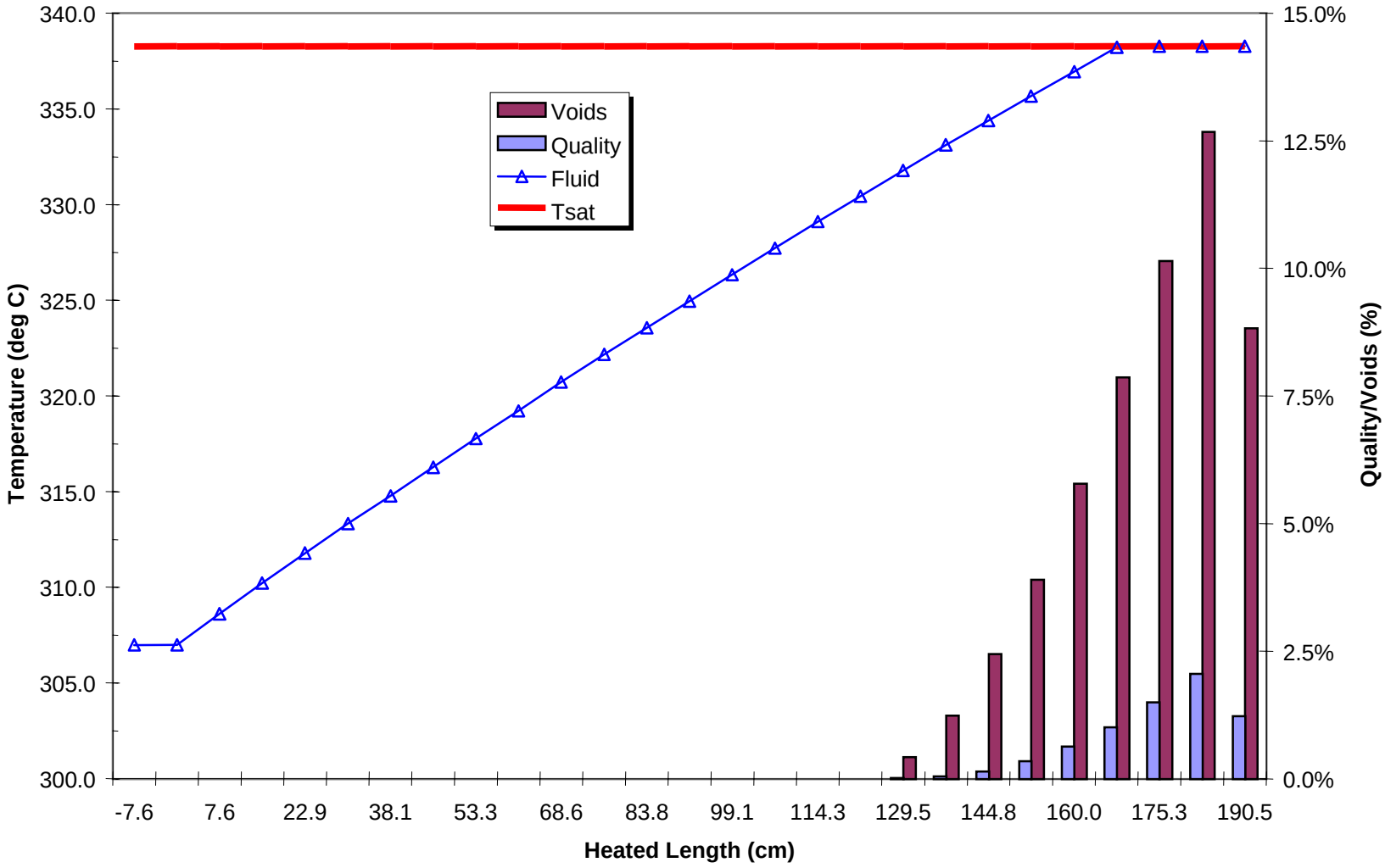


Figure 5-9
Injection Test 2000/03 Projected

5.4.2 Operation

Test 2000/03 started the 2nd of October 2000 with the new T/H conditions (see Table 5-17). The Ni and Fe injections began the 6th of October 2000 after 4 EFPD at the nominal conditions, with the related injection rates of 0.8 mg/hr and 0.2 mg/hr. An analysis of the primary fluid was undertaken just before the beginning of the Ni, Fe injections. A shutdown, without oxidation of the coolant, is foreseen about the 25th of October 2000

6
CONCLUSION

6.1 Summary Status

Several out-reactor tests in Cirene loop have been completed. These included four tests in 1998, two each in 1999 and 2000. Test 2000/03 is currently on going at the time of writing of this interim report. If necessary, the conditions for each of these tests were changed based upon the prior test results. The first tests were conducted under the prototypic PWR thermal duty without external injection. This was followed by the testing under somewhat more aggressive T/H conditions, but still without the external injection. Finally, controlled external injection was implemented while increasing the severity of the T/H conditions.

None of these tests generated an adequate thickness (i.e., ~ 5 μm) of crud deposition. Indeed the 1998 series of tests confirmed experimentally that the solubility driven crud deposition is negligible. With the required correction for "as-deposited" (i.e., before the shutdown) versus "as-scraped" (i.e., after the shutdown), the Ni/Fe ratio in the rather thin crud generated in 1998 and 1999 series tests was shown to be AOA representative crud.

The questions remain as to why thick crud was not generated even with external injection and why the crud with injection became Ni deficient? Further, why the crud tended to be deposit fairly uniformly throughout primary circuit rather than preferentially on the boiling surfaces? The answers to these questions are not clear at this stage.

The surface finish and roughness of the cladding are known to have an influence on the local T/H conditions (e.g., on the onset of the nucleate boiling) as well as on the initial rate of pre-transition oxide film formation. Similar dependence may also exist for the crud deposition in initially fresh claddings used in this program. In other words, regarding the thin crud found in this program, it is possible that there is a threshold exposure level necessary for rapid deposition of crud that may not have been reached yet.

The current exposure of the four claddings in the Cirene test section can be summarized as follows:

Table 6-1
Current exposure of the tests rods

Cladding No.	Cladding Type	Exposure (through test 2000/02), EFPD
1	Electropolished AFA2G	> 145
2	Recrystallized and non-electropolished Zry 4	145
3	Non-electropolished Zry 4	133
4	Non-electropolished Zry 4	70

After test 2000/01, only rod No. 4 was cleaned or brushed for crud sampling. The other 3 rods have not been cleaned or brushed. Thus they will continue to accrue exposure with subsequent testing and eventually could be expected to reach the exposure sufficient for rapid deposition like in the AOA core. This is clearly speculative at this stage and can be only proved or disproved experimentally with additional testing. Other hypotheses such as radiolysis, impact of O_2, etc. can also be explored or analyzed in the context of results obtained to date. Such reflections will improve our understanding of the deposition mechanism.

6.2 Future Plans

Additional testing is anticipated with improved diagnostics in 2001. Specifically, the following two areas of improvements of the test section (see Figure 6-1) are being implemented:

(a) In-situ visualization of bubble nucleation: A sapphire window will be installed on the pressure boundary wall of the heated section. This will facilitate direct observation of flow and boiling conditions in the upper elevation of the rod bundle.

(b) Pressure drop measurement: Differential pressure sensors will be installed at various locations over the heated section. This will enable various pressure drop measurements of interest, as shown in Figure 6-1. This feature will be especially interesting when thick crud begins to deposit. The device is available for Test 2000-3.

Ion injection could be performed using certain isotopically enriched radioactive tracer compounds of Ni and Fe rather than naturally occurring compounds currently used. This would allow us to distinguish between deposition originating from the external injection versus that released from primary circuit surfaces. While this is an interesting approach, it requires additional safety license to permit the use of new radioactive compounds. For the present, there are no plans to actually implement this suggestion.

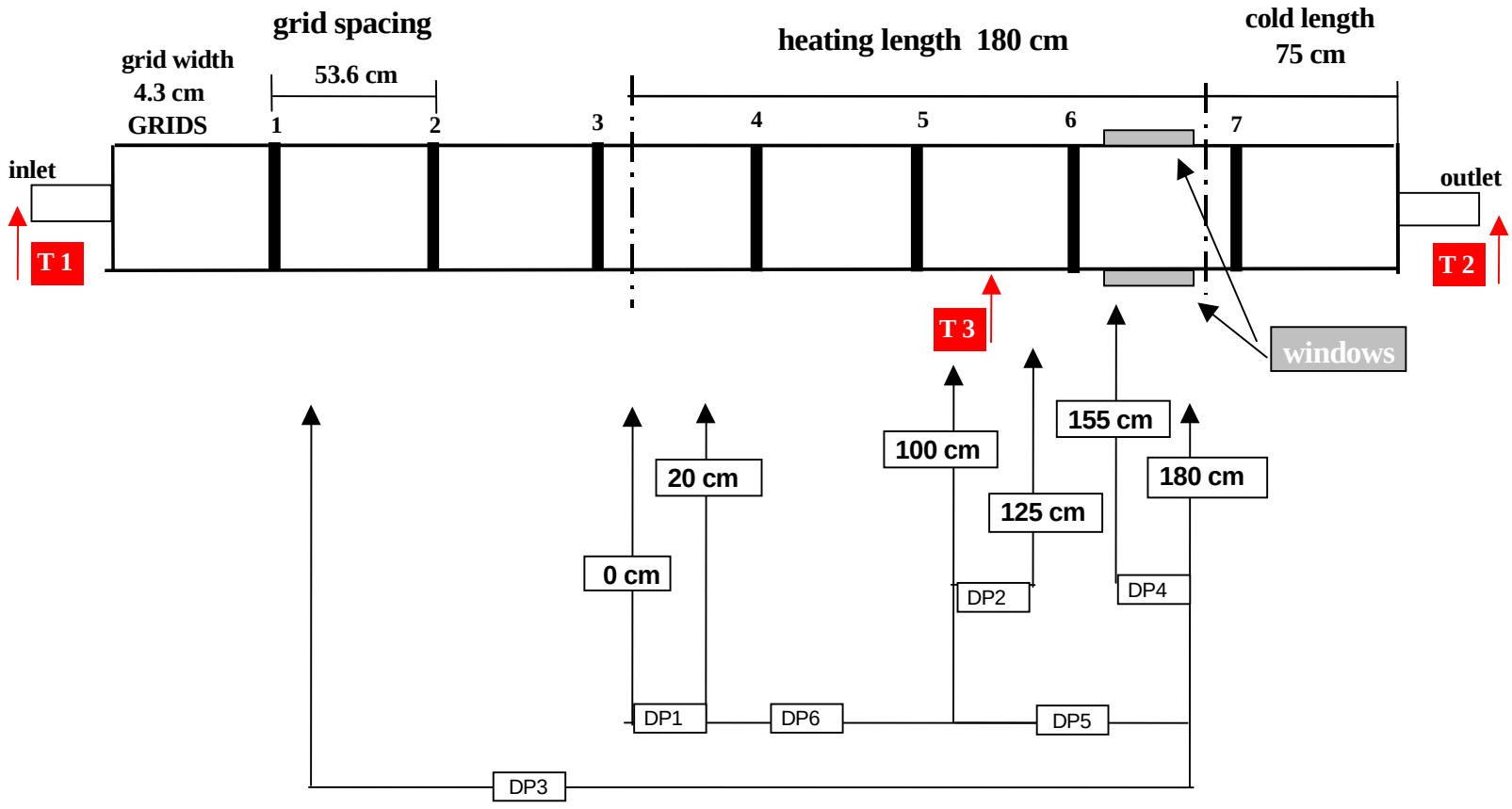


Figure 6-1
Cirene Test Section Adapted to in Situ Pressure Drop Measurements and bubble visualization

A
APPENDIX A: SELECTION OF TEST CONDITIONS FOR 1999/01

FLICA calculations are summarized in this Appendix for selecting optimum test conditions for 1999/01. The objective was to obtain the highest steaming rate possible within the operational limitations of the Cirene loop.

Both homogeneous and non-homogeneous heat fluxes were considered. The former was clearly preferred to avoid any difficulties later in the interpretation of the results.

Lowering the system pressure (at similar mass flow rate) increased exit evaporation rate but also decreases the cladding wall temperatures from 344.5°C at 150 bar, to 334°C at 130 bar. It was considered desirable to maintain the cladding wall temperature value close to 345°C to simulate a high duty PWR.

Taking into account the system limits, the preferred homogeneous heat flux, and cladding wall temperature ~ 345°C, calculations were performed by varying the mass flow rate and the inlet temperature.

The main results of the simulations are reported in the Tables I, II, III, and compared with the 9801/04 Cirene loop test.

The following discussion points are noteworthy:

(1) It was obvious that a very high steaming rate of, say, 5 000 kg/m^2.hr cannot be reached at the exit of the test section in the Cirene loop. Indeed, the global evaporation rate Gvap is linked to the evaporation flux, Φvap, and the latent heat of condensation, L, by the following relation:

$$Gvap = \Phi vap / L ,$$

thus with a heat flux of 100 W/cm^2 applied on the heating rods and a pressure of 150 bar, the highest evaporation rate that could be reached in the Cirene device is:

$$Gvap(kg/m^2.hr) = 36\,000 * 100(W/cm^2) / 1\,004(J/kg)$$

i.e. , only a maximum Gvap = 3 585 kg/m^2.hr is possible.

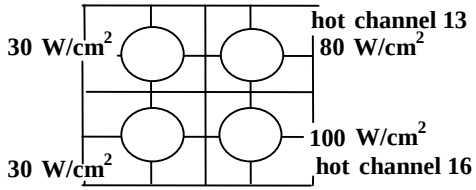
(2) The heat exchanger tube specificity of the Cirene loop, the inlet and outlet temperatures of the test section (T_{inlet} : 295-300 °C and T_{outlet} : 325-330°C), impose the maximum heat flux applied on the 4 heating rods around 75 W/cm^2. With such heat flux levels, the maximum evaporation rate Gvap=Φvap / L reaches a value of 2000 kg/m^2.hr in the hot sub-channel at the exit, which is too low to simulate a high evaporation rate test. The main results of these simulations are reported in the summary table enclosed (E, F, G, H references).

(3) In order to get an evaporation rate, Gvap, close to 3 500 kg/m^2.hr at the outlet of test section, it was necessary to apply various fluxes on the heating rods, remaining an average flux around 65 W/cm^2. Thus with 100, 80, 30 and 30 W/cm^2 of flux intensities, high evaporation rates from 2 760 to 3 465 kg/m^2.hr are reached in the hot sub-channel 16 relevant to the 100 W/cm^2 cladding. The results of these simulations are reported in the summary table enclosed (see A, B, C, D references).

CIRENE LOOP - Thermal-hydraulic conditions for high evaporation rate (with max.Gvap.=3 585 kg/m^2.hr)

Heat flux / heating rod

non homogeneous fluxes

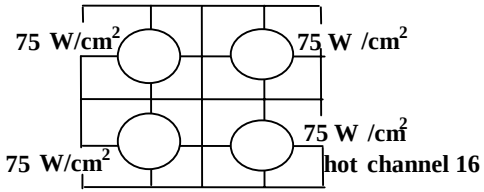


FLICA 4 thermal-hydraulic calculations (hot sub-channels 16 and 13)

Inlet pressure	Mass flow rate	Inlet temp.	Outlet temp.	Wall temp. °C		Exit Gvap. kg/m^2.hr		Exit void fraction %		Ref.
bar	g/cm^2.s	°C	°C	channel 16	channel 13	channel 16	channel 13	channel 16	channel 13	
150	250	300	325	344.5	344.4	2760	1630	2	0.8	A
	220	300	328.5	344.5	344.4	3215	2215	4.5	1.8	B
	200	300	331	344.5	344.4	3465	2430	9	3.2	C
150	220	295	325	344.5	344.4	2875	1750	2.5	1	D

Heat flux / heating rod

Homogeneous fluxes



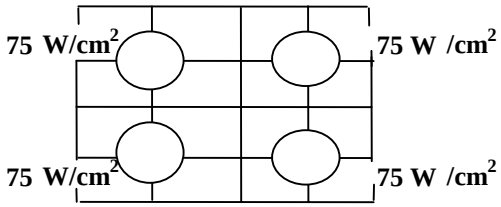
FLICA 4 thermal-hydraulic calculations (hot sub-channel 16)

Inlet pressure	Mass flow rate	Inlet temp.	Outlet temp.	Wall temp. °C		Exit Gvap. kg/m^2.hr		Exit void fraction %		Ref.
bar	g/cm^2.s	°C	°C	channel 16	channel 13	channel 16	channel 13	channel 16	channel 13	
150	250	300	331	344.5		1570		0.9		E
	225	300	334	344.5		1970		1.7		F
145	250	300	331	342		1780		1.3		G
	225	300	333.5	342		2130		2.6		H

TABLE I

CIRENE LOOP - Thermal-hydraulics conditions for high mass evaporation rate Gvap.(kg/m^2.hr)

Homogeneous fluxes



FLICA 4 thermal-hydraulics calculations in the hot sub-channel 16 (Gvap. versus turbulence coefficient)

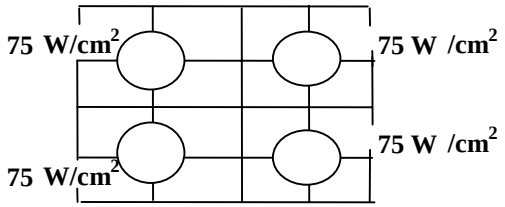
Inlet pressure	Mass flow rate	Inlet temp.	Outlet temp.	Wall temp.	Exit Gvap.*	Ref.
bar	g/cm^2.s	°C	°C	°C	kg/m^2.hr	
150	250	300	331	344.5	1665 - 1990	150A
	225	300	334	344.5	2050 - 2335	150B
	200	300	337	344.5	2420 - 2615	150C
	250	305	335	344.5	2075 - 2350	150D
	225	305	337.5	344.5	2400 - 2600	150E
	200	305	340	344.5	2640 - 2715	150 F
	250	310	338.5	344.5	2450 - 2630	150G
	225	310	340.5	344.5	2650 - 2715	150H
	200	310	342	344.5	2720 - 2725	150I
150	250	310	337.35	344.5	2130 - 2350	9801/04 test

Exit Gvap.* : estimated with Kt=0.01 and Kt=0.003 turbulence coefficients

TABLE II

CIRENE LOOP - Thermal-hydraulics conditions for high mass evaporation rate Gvap.(kg/m^2.hr)

Homogeneous fluxes



FLICA 4 thermal-hydraulics calculations in the hot sub-channel 16 (Gvap. versus turbulence coefficient)

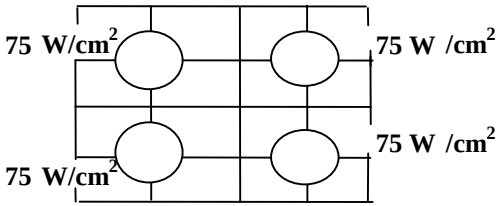
Inlet pressure	Mass flow rate	Inlet temp.	Outlet temp.	Wall temp.	Exit Gvap.*	Ref.
bar	g/cm^2.s	°C	°C	°C	kg/m^2.hr	
145	250	300	331	342	1860-2160	145A
	225	300	333.5	342	2200- 2445	145B
	200	300	336.5	342	2500-2600	145C
	250	305	334.5	342	2250-2470	145D
	225	305	337	342	2500-2605	145E
	200	305	338.8	342	2620-2635	145 F
	250	310	337.8	342	2540-2620	145G
	225	310	339	342	2625-2640	145H
	200	310	339.5	342	2640-2640	145I
150	250	310	337.35	344.5	2130 - 2350	9801/04 test

Exit Gvap.* : estimated with Kt=0.01 and Kt=0.003 turbulence coefficients

TABLE III

CIRENE LOOP - Thermal-hydraulics conditions for high mass evaporation rate Gvap.(kg/m^2.hr)

Homogeneous fluxes



FLICA 4 thermal-hydraulics calculations in the hot sub-channel 16 (Gvap. versus turbulence coefficient)

Inlet pressure	Mass flow rate	Inlet temp.	Outlet temp.	Wall temp.	Exit Gvap.*	Ref.
bar	g/cm^2.s	°C	°C	°C	kg/m^2.hr	
140	250	300	330.5	339	2050-2300	140A
	225	300	333	339	2335-2490	140B
	200	300	335.5	339	2520-2550	140C
	250	305	334	339	2385-2510	140D
	225	305	335.75	339	2520-2550	140E
	200	305	336.5	339	2555-2560	140 F
	250	310	336.25	339	2540-2560	140G
	225	310	337	339	2560-2560	140H
	200	310	337	339	2560-2560	140I
138	250	300	330.3	338.2	2050 - 2380	E
150	250	310	337.35	344.5	2130 - 2350	9801/04 test

Exit Gvap.* : estimated with Kt=0.01 and Kt=0.003 turbulence coefficients

B
APPENDEX B: FLICA CALCULATIONS FOR TEST 2000/01

Figure B-1 shows the axial evolution of the expected evaporation rate for the 2000/01 test in the hot and average sub-channels. Figure B-2 and B-3 show the global evaporation rates and the void fractions which are respectively expected in the hot, and in the average sub-channels. The main results of the FLICA 4 thermal-hydraulic simulations are also tabulated in Table B-1 and Table B-2.

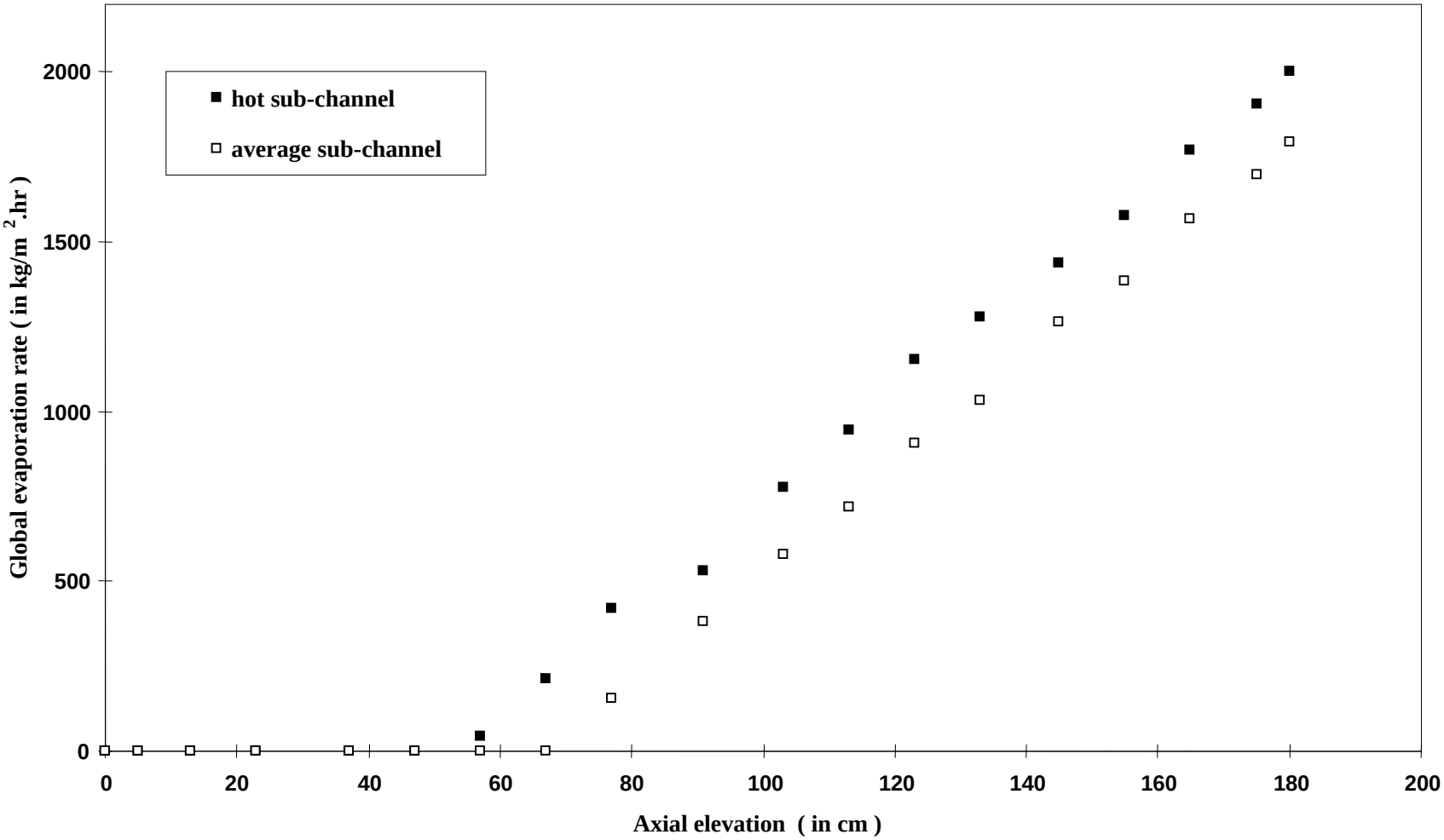


Figure B-1
Global Evaporation Rates in The Average And Hot Sub-Channels (Flica 4 Calculations)

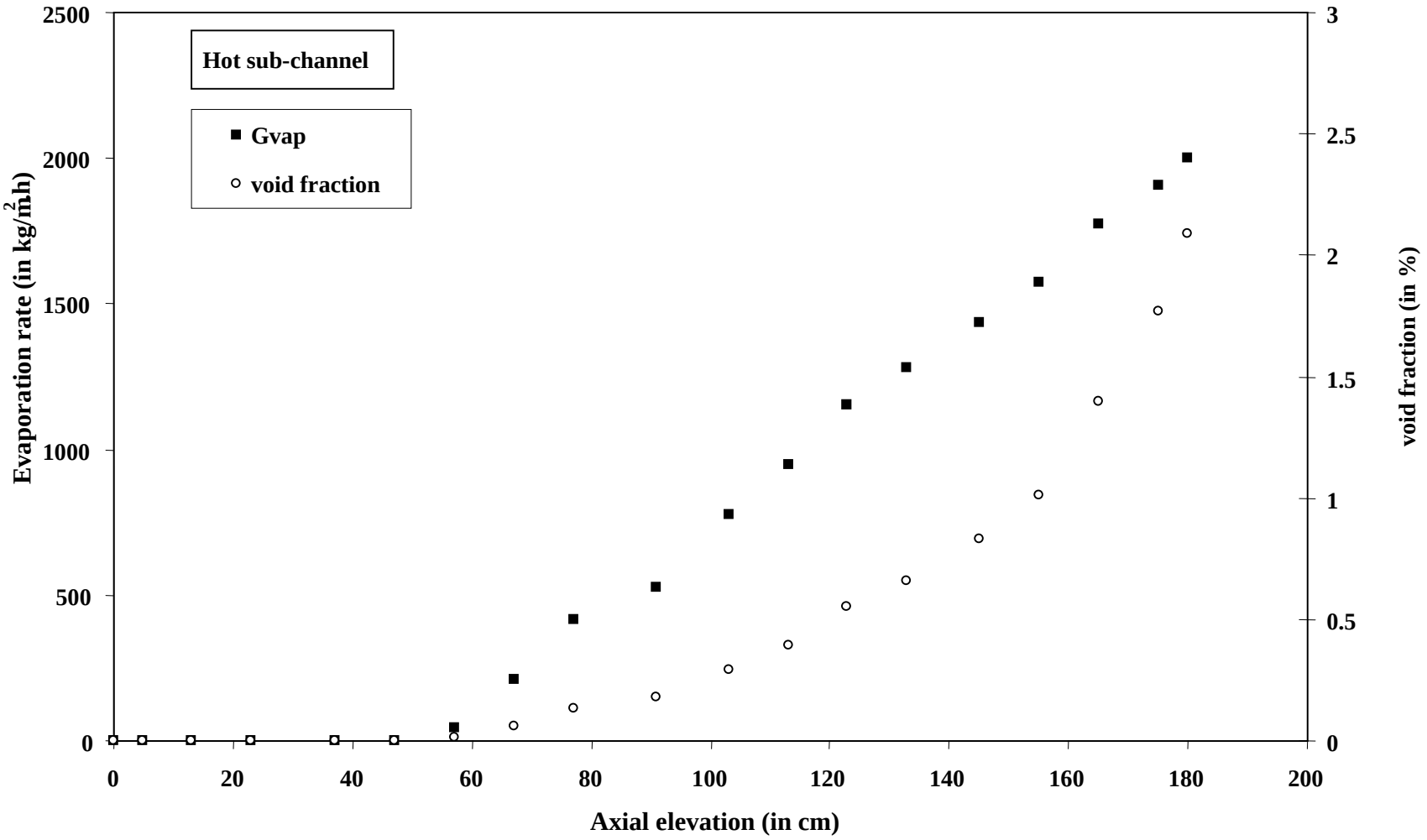


Figure B-2
Global Evaporation Rate and Void Fraction in the Hot Sub - Channel (Flica 4 Calculations)

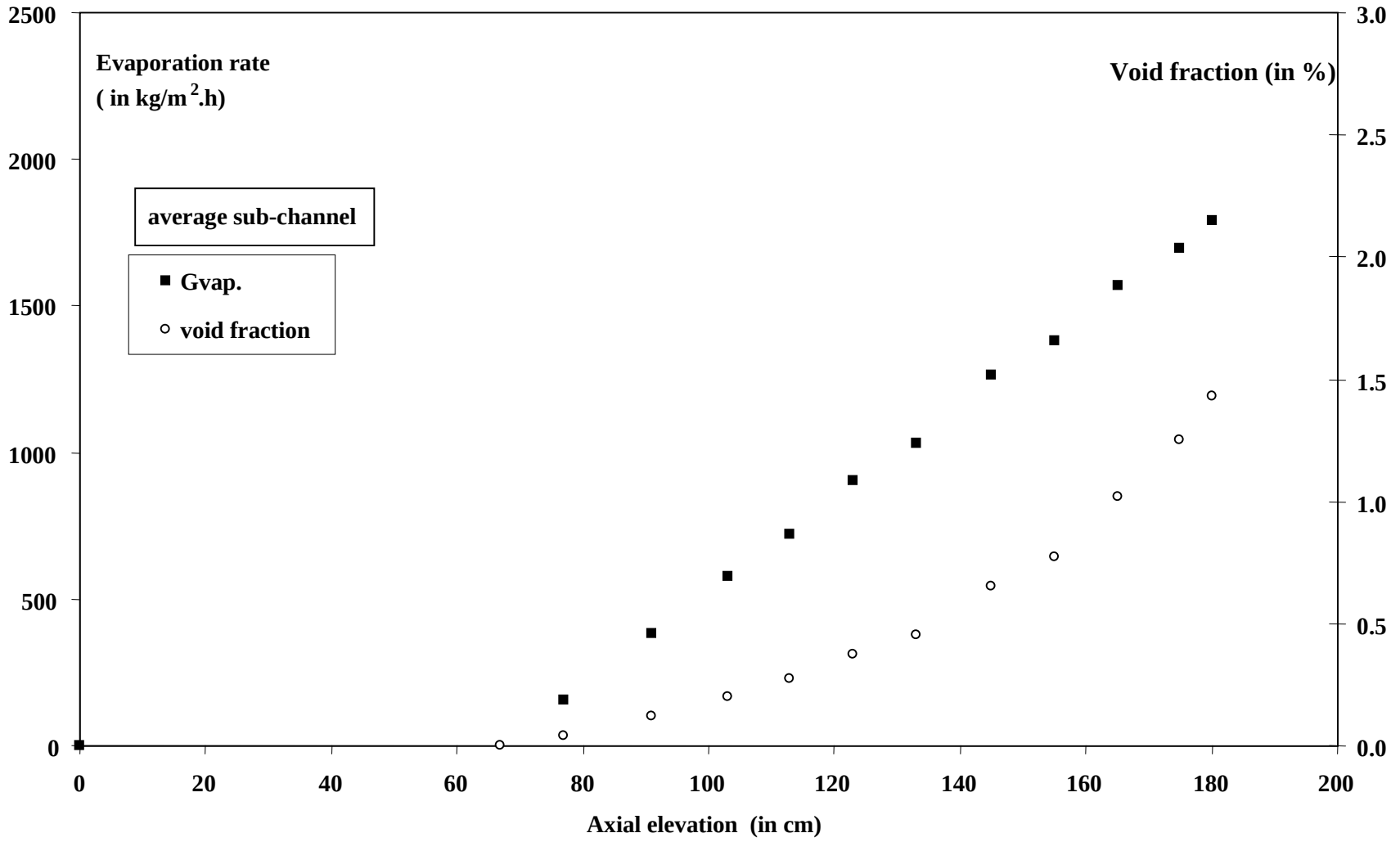


Figure B-3
Global Evaporation Rate and Void Fraction in the Average Sub - Channel (Flica 4 Calculations)

Table B-1
Cirene Test 2000/01 Calculated Evaporation Rate, Void Fraction, Wall and Fluid Temperatures in average sub-channel

axial elevation cm	Gvap kg/m² hr	Gvap 10^{-3}g/cm².s	void fraction %	fluid temperature °C	wall temperature °C
0	0			310	310
5	0			311	334.5
13	0			312.3	336.2
23	0			314	337.5
37	0			316.3	340.2
47	0			317.8	341.2
57	0			319.5	343.15
67	0	0	0	321	344.4
77	154.5	4.3	0.04	322.5	344.6
91	380	10	0.12	324.7	344.6
103	577.5	16	0.2	326.4	344.6
113	721	20	0.27	328	344.6
123	905.5	25	0.37	329.3	344.55
133	1031	29	0.45	330.7	344.55
145	1262	35	0.65	332.3	344.5
155	1382.5	38	0.77	333.7	344.5
165	1570	43.5	1.02	334.9	344.5
175	1697	47	1.25	336.3	344.5
180	1793	50	1.43	336.9	344.5

Pressure = 150 bar, Heat flux = 70 W/cm^2
Inlet mass flow rate = 250 g/cm^2.s
Test section inlet temperature = 310°C

Table B-2
Cirene Test 2000/01 Calculated Evaporation Rate, Void Fraction, Wall and Fluid Temperatures in hot sub-channel

axial elevation cm	Gvap kg/m² hr	Gvap 10^{-3}g/cm².s	void fraction %	fluid temperature °C	wall temperature °C
0	0.00	0.00	0.00	310.00	310.00
5	0.00	0.00	0.00	311.00	334.15
13	0.00	0.00	0.00	312.40	336.50
23	0.00	0.00	0.00	314.26	338.53
37	0.00	0.00	0.00	316.74	340.73
47	0.00	0.00	0.00	318.45	342.45
57	43.50	1.20	0.01	320.18	344.65
67	212.00	5.90	0.06	321.90	344.60
77	418.00	11.60	0.13	323.60	344.60
91	529.00	14.70	0.18	325.80	344.60
103	778.20	21.60	0.29	327.60	344.60
113	946.50	27.00	0.39	329.10	344.60
123	1151.00	32.00	0.55	330.60	344.60
133	1279.00	35.50	0.66	332.00	344.60
145	1436.50	40.00	0.83	333.70	344.50
155	1576.60	43.80	1.01	335.00	344.50
165	1773.00	49.00	1.40	336.30	344.50
175	1904.80	53.00	1.77	337.60	344.50
180	2000.00	55.50	2.09	338.15	344.50

Pressure = 150 bar, Heat flux = 70 W/cm^2
Inlet mass flow rate = 250 g/cm^2.s
Test section inlet temperature = 310°C

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