DESIGN AND CONSTRUCTION OF A ZIRCALOY PRESSURE VESSEL FOR THE CABRI RESEARCH REACTOR

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ABSTRACT:

The Cabri Research Reactor, located at the Cadarache nuclear research center, is operated by CEA/DER and is devoted to IRSN safety programs. A new experimental loop to recreate the thermohydraulic conditions equivalent to those of a pressurised water reactor was implemented under the Cabri International Program (CIP) carried out by IRSN as part of an OECD agreement. The experimental vessel connected to the loop and receiving samples goes through the core of the reactor. For reasons of neutron transparency, the vessel and its containment have been made of zirconium alloy, which provides better neutron coupling between the core and the sample tested.

The CEA launched the development of the RCC-MX code (Design and Construction Code for Research Reactors) in 1998. As these rules were not available when the CABRI construction phase was launched, the vessel was designed and constructed to resist to 190 bars and 355°C with specific rules providing a quality level equivalent to the RCC-M level 1.

The definition, justification and implementation of these specific rules (Zircaloy is not referenced in the RCC-M Code) are presented with emphasis on all phases of production: procurement, mechanical characterisation, fabrication, welding and inspection. Mechanical properties are mainly issued from experimental testing performed specially for this project, while construction rules come from industrial practices and EN or ISO standards. This presentation also establishes the link with the experience feedback which profit to the RCC-MX Code and to the future release of RCC-MRx Code.

ABREVIATIONS

ASTM: American Society for Testing and Material

CEA: French Atomic Energy and Alternative Energies Commission

CIP: Cabri International Program

DEN: Nuclear Energy Division of CEA

DER: Reactor Studies Department of DEN

DT: Destructive testing

EB: Electron Beam

HIP: Hot Isostatic Pressing

IRSN: Institut de radioprotection et de sûreté nucléaire (Institute for Radiation Protection and Nuclear Safety)

NDE: Non-Destructive Examination

OECD: Organization for Economic Co-operation and Development

PCS: Probe Centre Separation (distance between ultrasound beam emission points)

PWR: Pressurised Water Reactor

RCC-M: Design and Construction Code for PWR mechanical materials

RCC-MX: Design and Construction Code for mechanical materials of Research Reactors

RCC-MR: Design and Construction Rules for mechanical components of Nuclear Installations

RIA: Reactivity-Initiated Accident

SFR: Sodium Fast Reactor

TIG: Tungsten Inert Gas

TOFD: Time-Of-Flight Diffraction

INTRODUCTION

The CABRI Research Reactor located at the CEA/Cadarache site is used to conduct safety studies on the fuel rod behaviour (cladding and fuel) in Reactivity-Initiated Accident (RIA) conditions. Although the facility was initially designed for Sodium-cooled Fast Reactor (SFR) fuels, it has since been significantly adapted for fuel studies on water-cooled reactors as part of the CABRI international water loop project carried out by IRSN under an OECD agreement.

In the tests carried out on this reactor, the fuel rod sample is subjected to a fast power transient representative of a control rod ejection accident.

Cabri is a pool-type reactor comprising:

- A forced (water) flow cooled breeder core with power limited to 25 MWth in continuous operation,
- A test loop,
- A system capable of generating brief high power peaks in the breeder core rods, instantly transferred to the test fuel.

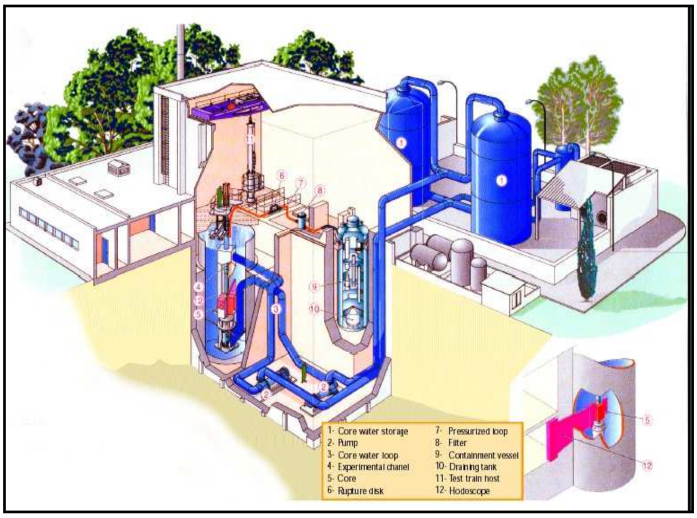


Figure 1: Artist’s impression of the Cabri facility

One of the main changes to the facility involved replacing the test loop. Built under the supervision of AREVA NP, the test loop:

- Receives and positions the test device in the centre of the breeder core. The device is a mobile, consumable element containing the test fuel rod,
- Provides the required thermohydraulic conditions for the test fuel rod,
- Forms the primary and secondary containment barriers around the test fuel rod.

The work described below mainly concerns the components of the loop which contains the test fuel rod and goes through the breeder core. These components are made of zirconium alloy for reasons explained in the second section.

The RCC-MX Code (Design and Construction Code for mechanical materials of Research Reactors) developed by the CEA was not available when the CABRI construction phase was launched, so the vessel – designed to resist to 190 bar and 355°C – and its containment were built according to a quality level equivalent to Level 1 of the RCC-M code (Design and Construction Code for PWR mechanical materials).

Since Zircaloy is not referenced in the RCC-M, the definition, justification and implementation of these specific rules are presented with emphasis on all project phases: procurement, mechanical characterisation, fabrication, welding and inspection. Mechanical properties are mainly issued from experimental testing performed specially for this project, while construction rules come from industrial practices and EN or ISO standards. This presentation also establishes the link with the experience feedback which profit to the RCC-MX Code and to the future release of RCC-MRx Code*.

THE TEST LOOP AND ITS CONTAINMENT

The principal purpose of the test loop is to reproduce experimental conditions similar to those which occur in PWRs. The nominal operating conditions are:

- Pressure of 155 bar,
- Temperature of 300°C,
- Velocity of 4 m/s.

These conditions are covered by the design conditions (pressure of 190 bar and a temperature of 355°C) allowing common operational incidents.

The main safety function, i.e. containment, is defined on the basis of the potential consequences of the test. Under the effect of the power transient, it can lead to deterioration of the fuel cladding and ejection of the fuel into the primary system water. This primary system therefore forms the primary containment barrier and is installed inside a second shell.

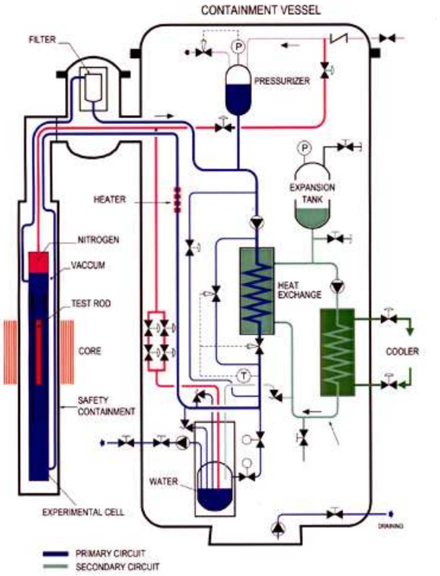


Figure 2: Schematic diagram of Cabri loop

The primary system and its shell consist of two non-mobile components:

1. The ‘in-pile’ reactor unit, located along the vertical axis of the breeder core. It consists of two concentric tubes: the central primary containment vessel (first barrier) and the safety tube (second barrier), separated by vacuum. This double containment creates thermal insulation between the primary containment vessel (300°C) and the pool reactor water (20-40°C).
2. The hydraulic components (e.g. primary pump, pressuriser, heat exchangers) located inside a containment vessel, along with a system of double-walled pipes to connect them to the reactor unit through a filter that collects any fuel particles which might be released into the loop.

This paper focuses on the primary containment vessel and its safety tube, both of which are made of zirconium alloy.

The test principle is to couple the Cabri reactor’s breeder core neutronically with the fuel sample being tested, which means it is essential to keep neutron shielding between the two components to the strict minimum. For this reason, Zircaloy-4 was chosen as the material for the reactor unit structures. It is relatively neutron transparent, which improves coupling while exhibiting the high mechanical properties required for the structural design loads, including pressure. Moreover, zirconium-based alloys are used on a standard basis as fuel cladding material, and more occasionally as structural material in specific applications in the nuclear and chemical industries, which gives access to a documentary base that covers numerous issues.

The choice of this material for the reactor unit made it necessary to develop heterogeneous Zircaloy/stainless steel joints for connection with the other systems made of austenitic steel, seeing that welding the two materials together using standard procedures is impossible. Heterogeneous joints using hot isostatic pressing (HIP) were developed and qualified. This specific subject is not discussed in this paper.

Description of structures

The primary containment vessel (Figure 4) is an 8980 mm-long cylinder. The cylinder's upper flange rests on the top of the safety tube. This suspended containment arrangement allows the structures to dilate during heating.

From top to bottom, the cylinder comprises sections with inner diameters of 145, 140, 138, 98, 96, 92, 85, 82 and 71 mm. Its thickness varies between 22.5 and 15.5 mm. Various nozzles are connected to it, the main ones being:

- Pressurised water inlets (4 tubes 11.176 mm in diameter), at the -8857-mm level,
- Pressurised water outlet (1 tube 31.75 mm in diameter), at the -5314-mm level,
- Gas nozzles (tube 11.176 mm in diameter), at the -3851-mm and -4220-mm levels.

An air exchanger was incorporated into its central part (from -3875 mm to -4571 mm) to cool the test device's seals areas if necessary.

At the -7680-mm and -6240-mm levels, 2 outer rings keep the lower part of the primary containment vessel centred in the safety tube, with a radius tolerance of 0.5 mm.

The safety tube (Figure 3) consists of two tubes connected by a cone at the -5200-mm level.

The top tube has an inner diameter of 380 mm and is 9 mm thick, while the bottom tube has an inner diameter of 154 mm and is 7 mm thick.

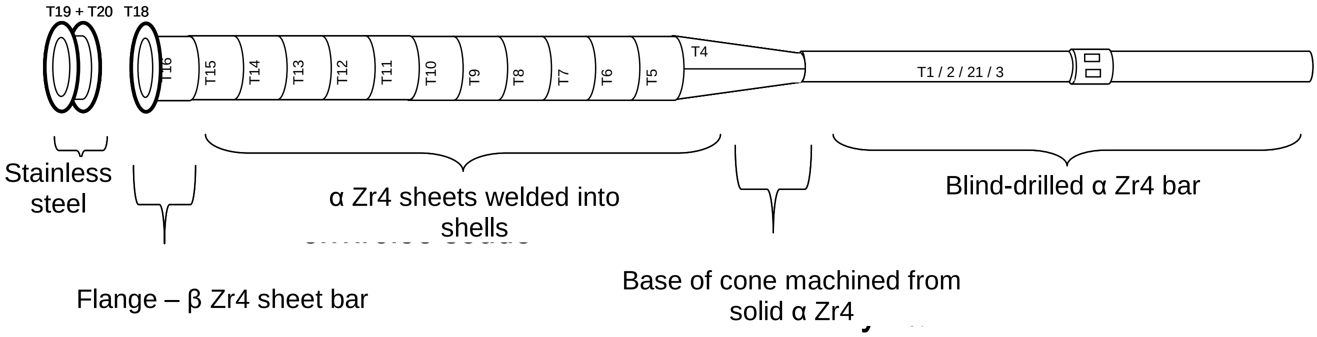


Figure 3: Safety tube - Materials

ZIRCALOY – PROCUREMENT

Zircaloy 4 was chosen as the zirconium alloy grade due to its good mechanical properties and corrosion resistance. Zircaloy 4 is also routinely used as fuel cladding material, which facilitates procurement. Moreover, the CEA has already used the grade in the past to build experimental devices, which means these material characterisation reports were available.

ASTM's grade R60804 was chosen as the general chemical composition. However, to improve the mechanical strength and creep-resistance properties for the bars used in the neutron flux area, the specification for the chemical composition was adjusted as follows:

- Target tin content was set at 1.7%, corresponding to the ASTM upper limit,
- Target oxygen content was set at 0.16%, also the ASTM upper limit,
- Specification not in ASTM for the sulphur content (10-50 ppm) was also defined.

Another specific feature of the bars used in the neutron flux area is attributable to the bars' metallurgical state upon delivery. Although Zircaloy 4 products are usually delivered in recrystallised state, the bars were delivered in a beta state due to a quench treatment performed after the forging operations. Such a quench treatment in the final stage effectively erases the anisotropy that is created by grain orientation during forging operations. As a result, the mechanical properties are much more homogeneous in both directions (length and width), while the alloy generally shows a marked difference.

To meet the fabrication requirements, four different products were supplied:

- Bars with diameters ranging from 140 mm to 230 mm,
- Parallelepiped-shaped forged parts sized 540 x 540 x 100 mm,
- Plates 445 mm wide (the limit set by supplier capability), 7 to 12 mm thick, and up to 3 meters long,
- Tubes with outer diameters from 11 mm to 32 mm.

The procurement of bars, plates and forged parts raised no particular problems, as they are in the category of finished or semi-finished products that are routinely supplied and inspected. Furthermore, acceptance inspections and other tests showed that the products were adequately homogeneous. Launching the procurement of tubes, however, required a lot more investment, and the technical specifications (especially the specific acceptance requirements) required considerable dialogue with the manufacturer because the dimensions of the smaller tubes (11 mm in diameter and 1.5 mm thick) were not standard.

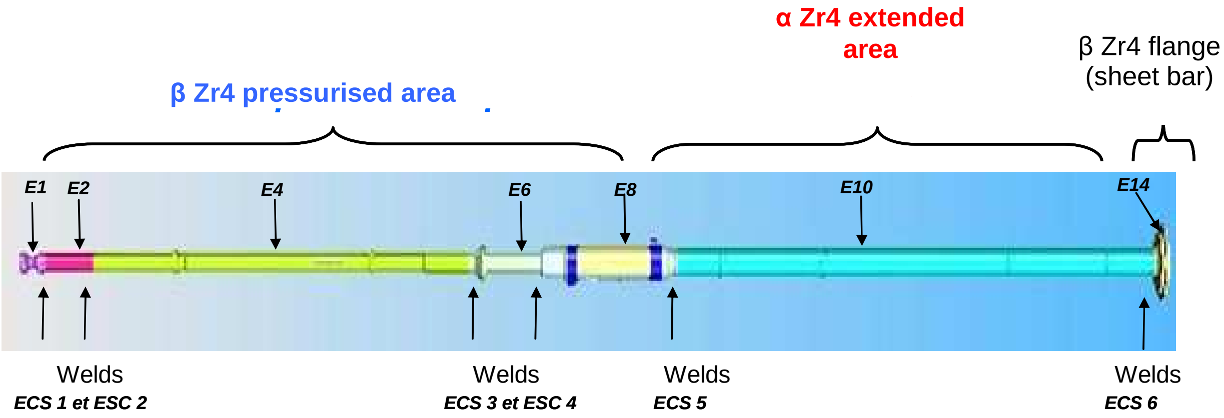


Figure 4: Primary containment vessel – Materials & welding

ZIRCALOY – CHARACTERISATION

Considerable effort was put into characterising the material and collecting data to confirm the suitability of the chosen design values. Besides the standard tensile properties, special attention was given to the tenacity properties and, to a lesser extent, the fatigue and creep properties.

Because the database was gradually built up as data was collected and the materials were tested, the project did not immediately benefit from an overall view of the material properties. As design data needs emerged, six sets of specific Cabri data were determined as a function of the product types and metallurgical state. Within the scope of this paper, we chose not to present the data sets individually, but rather to situate the minimum values from the 2008 RCC-MX Code with reference to the database. The Code uses an ASTM R60804 Class 1 (1,000-1,500 ppm) composition zirconium-based alloy in the recrystallised state as baseline reference. The results presented are based partly on this type of product, but they also cover structures in the beta-quenched state. No distinction is made between the different types of product (bar, plate, or forged part) or between the sample directions. Although these aspects do influence the mechanical properties of Zircaloy, they are not specified in the X3 Appendix of the Code providing minimum values.

Tensile properties

More than 700 tensile tests were recorded, with more than half being performed on products manufactured for the Cabri project. Fifteen different Zircaloy-4 castings were tested. As Figure 5 shows, all points for tensile strength (all products lumped together) fall within the minimum curve for the RCC-MX Code. A 30-40 MPa margin with respect to the minimum curve is observable in the 20°C-200°C range. This observation remains valid when comparing recrystallised products only. The conclusions concerning the yield strength are similar: all points fall within the minimum curve and there is a margin in the 20°C-200°C range, although a bit lower at about 20 MPa (Figure 6). Further analysis is required for elongation values for which the RCC-MX values appear to be close to the limit for the material's properties.

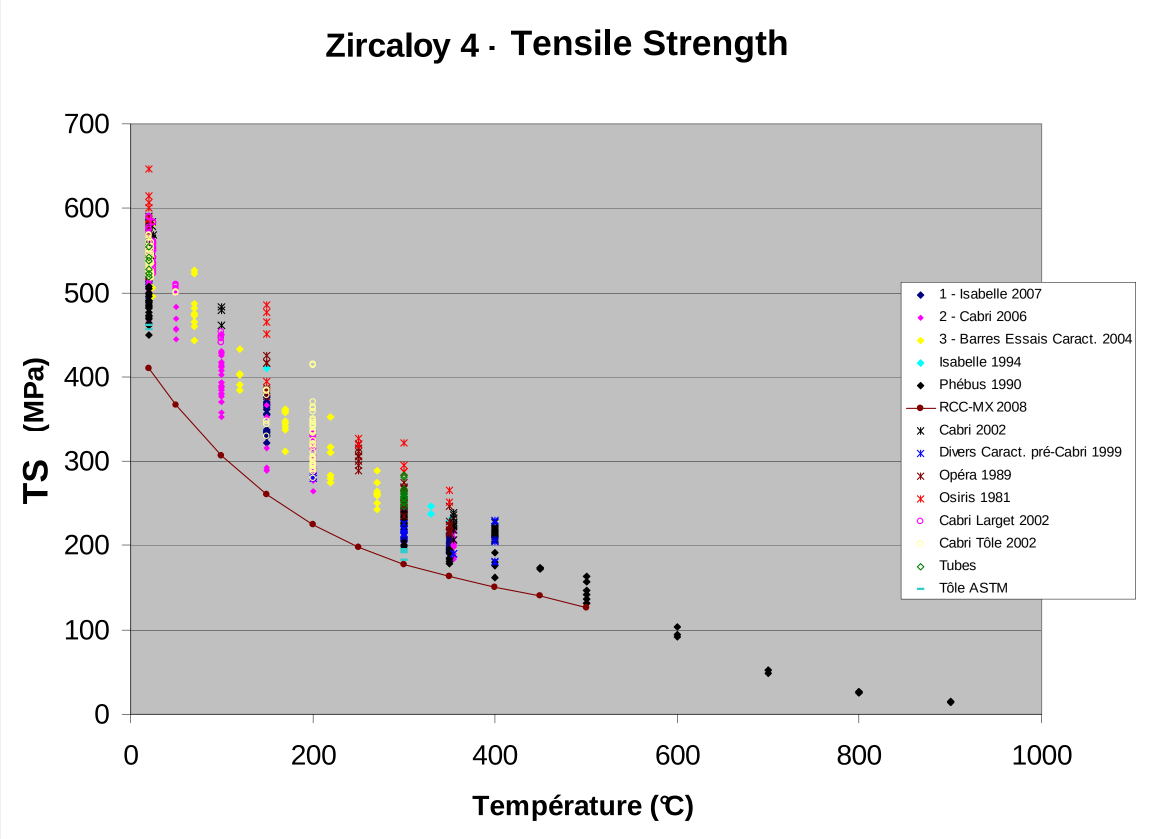


Figure 5: Zircaloy 4 – Tensile strength

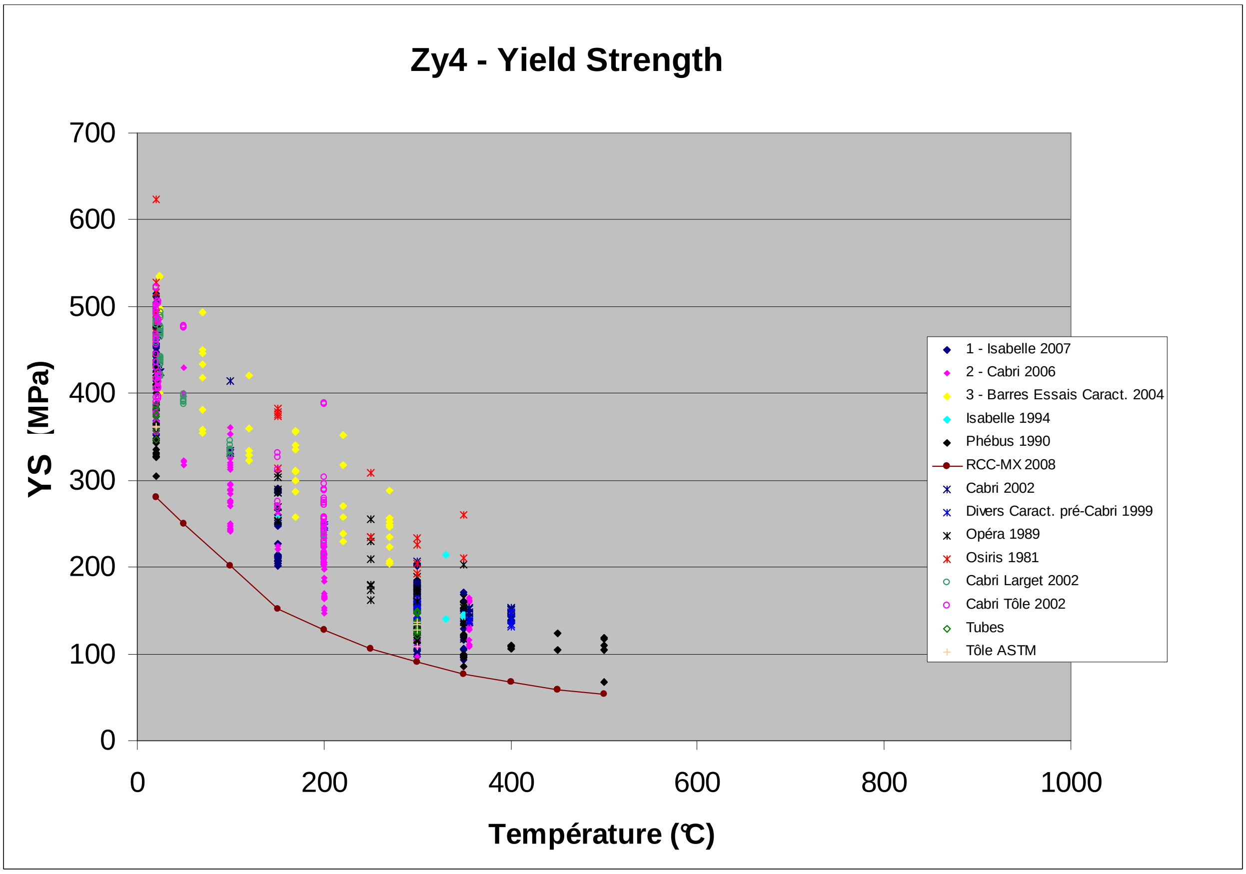


Figure 6: Zircaloy 4 – Yield Strength

Focus is placed on the specific procurement for the neutron flux area. Modifications to the chemical composition and to the heat treatments served to increase the mechanical properties. For the yield strength at 20° and 300° and for tensile strength at 20°, a 50 MPa increase was observed for the minimum values measured. A lower increase (+25 MPa over the minimum value) was observed for tensile strength at 300°C.

Toughness properties

An extensive toughness characterisation program was carried out on Zircaloy 4. The program involved more than 200 tests, with half being performed at ambient temperature. These tests not only focused on different product types and castings, but also on various welds using one of the following processes: electron beam, TIG or plasma.

Figure 7 shows that whatever the product or casting, and whether it is the base metal or the welds which are under consideration, the minimum toughness measured is always low, in the 30-40 KJ/m^2 range, while the maximum toughness is extremely scattered, by as much as a factor of four.

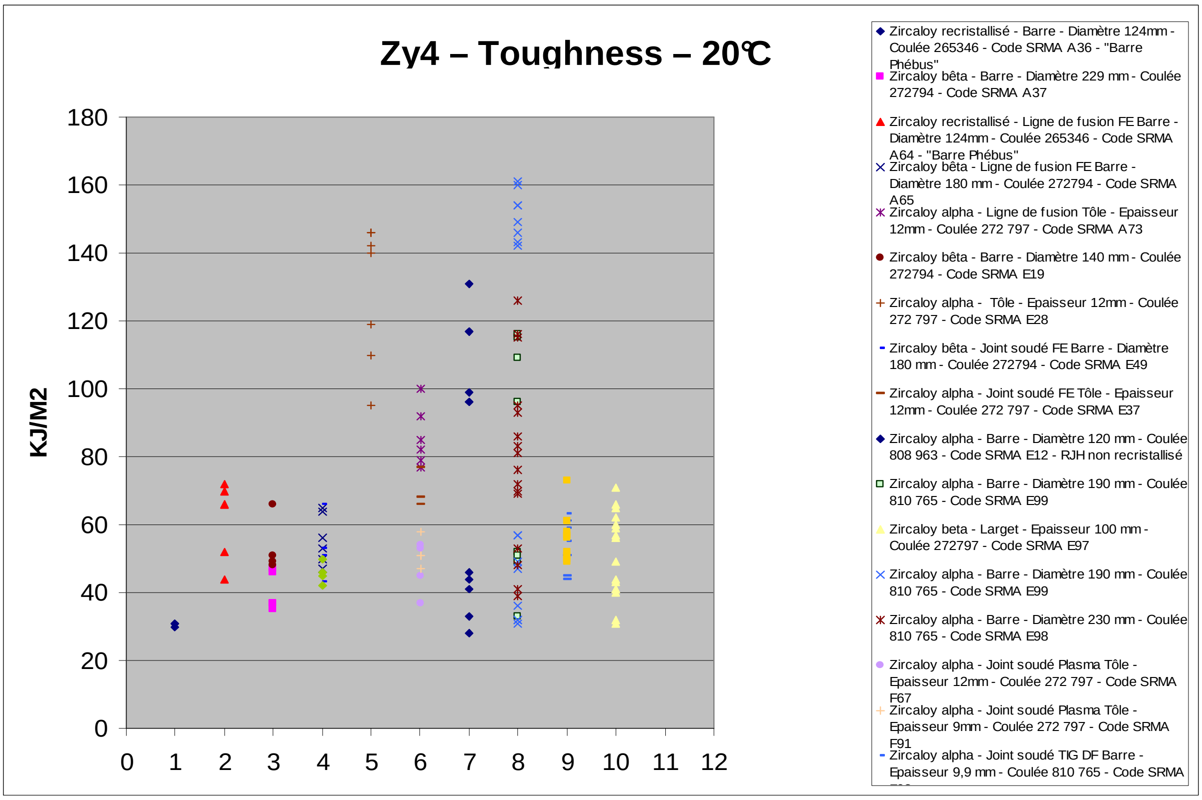


Figure 7: Zircaloy 4 – Toughness at room temperature

As Figure 8 shows, the variation of toughness as a function of temperature is not strongly significant at temperatures below 100°C.

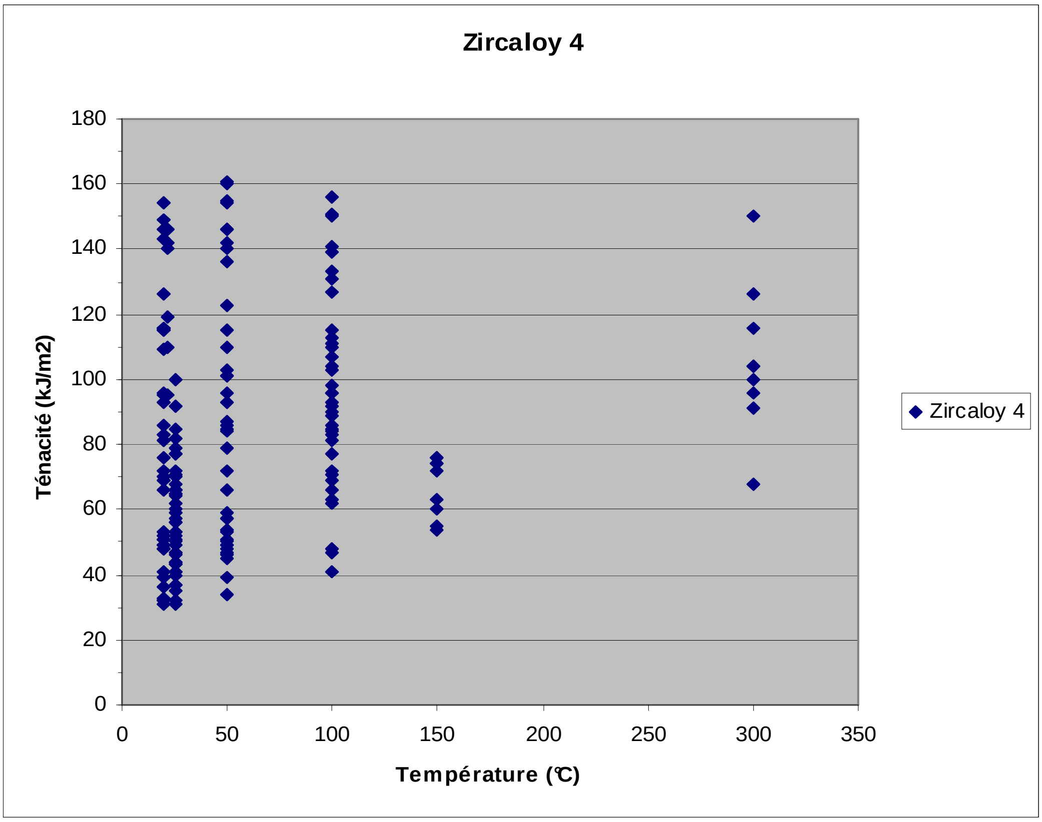


Figure 8: Variation in toughness as a function of temperature

Fatigue and creep properties

The project uses data from fatigue and creep characterisation tests on recrystallised Zircaloy 4 that were originally performed to support the design studies of the original sodium-cooled Cabri loop. Additional studies were carried out to verify that these values did in fact cover the Cabri products, notably the beta products. This involved performing creep tests at temperatures of 300, 350, 375 and 400°C with stress levels that led to failure within a time limit from several hundred hours to thousands of hours (this range being adapted to the length of time the structures were expected operate in the reactor).

Various fatigue tests made it possible to:

- Establish a fatigue curve at 400°C,
- Establish a Paris law at 300°C,
- Verify that the properties used were in fact applicable to the welded joints.

During each of these characterisation campaigns, the properties were compared systematically with the RCC-MX values and revealed no inconsistencies.

PRIMARY CONTAINMENT VESSEL – FABRICATION

Adapting the fabrication reference system

The RCC-M code applicable to the project needed to be adapted in relation to Zircaloy-4 before any fabrication operations or process qualification could begin.

Adaptations to the fabrication reference system concerned the following topics:

- **Hardness tests**: defining a maximum permissible hardness at 260 HV10,
- **Bend tests**: changing the diameter of the bending mandrel to 10 X thickness,
- **Corrosion tests**: defining corrosion tests according to ASTM G2,
- **Radiographic examinations**: using a zirconium hole-type image quality indicator according to ASTM E1025 in coherence with the thicknesses and the use of X-rays,
- **Liquid penetrant tests on bevels**: replacing liquid penetrant examinations by reinforced visual inspections to avoid pollution issues,
- **Welding qualification**:
  - defining the conditions for qualification of welding procedures,
  - applying the NF EN ISO 9606-5 standard for welder qualifications,
  - defining acceptance procedures for Zircaloy-4 filler metals. The wires used during qualification are qualified based on the qualification results. An additional chemical analysis (outside the dilution zone) is performed according to ASTM E146 and for the values specified for ASTM B350’s UNS grade R60804,
- **Forming qualification**: requirement to qualify forming procedures for all elongations and to define the qualifications conditions applicable to the forming procedures,
- **Cleaning procedures**: defining the conditions for cleaning procedures, including the pickling of Zircaloy-4.

Forming

The safety tube is made of a multitude of 9 mm thick formed-welded sheets constituting the cone and the upper part. Qualification procedures were applied to the roll-bending process for shells 348 mm in diameter and 9 mm thick, and to the press-forming process for the cone’s smallest diameter at 223 mm x 9 mm thick (greatest elongation). After qualification, the level of accuracy on the 348 mm diameter shells is roughly a millimetre.

The three dimensions of the primary containment vessel pipes (Φ 11.176 x 1.55 mm thick; Φ 20 x 1.35 mm thick; Φ 31.75 x 5.03 mm thick) are bent at the expansion loops and various elbows levels. For each dimension, the bending process is qualified.

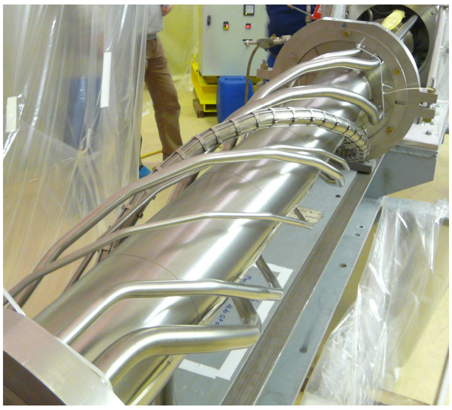


Photo 1: Expansion loops

Photo 2: Bending tests

The press-bending procedure to form the closing shell of the primary containment vessel air exchanger (Φ 222 x 4 mm thick) was qualified.

All forming and bending procedures performed on the primary containment vessel and the safety tube were cold processes. The forming processes were not subjected to stress relief annealing. The main problem encountered was adapting the forming mandrel diameter to avoid exceeding the product's deformation capacities.

The non-destructive examinations (NDE) applied to qualification forming procedures were identical to the production forming tests, and included the following inspections:

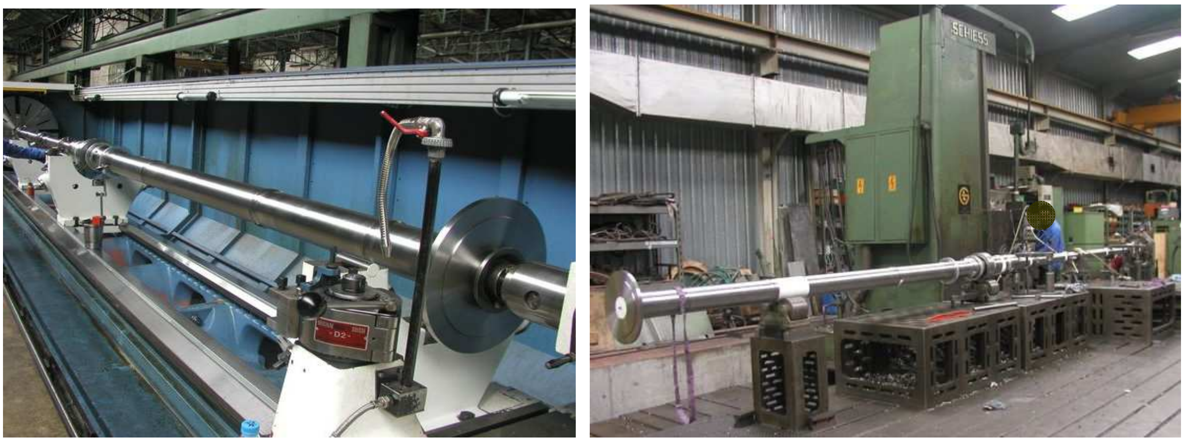
- Pre-forming: visual inspection and liquid penetrant tests of the plates and tubes,
- Post-forming and welding: visual inspection and liquid penetrant tests of the bent areas, where possible on both faces, and geometric tests on the forming using a template.

Photo 3: Post-forming inspection using a template

Machining (drilling & lapping)

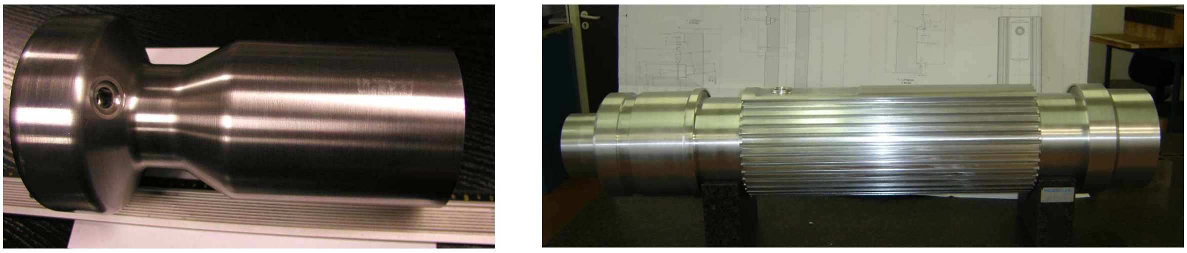
The lower part of the safety tube is machined in a bar blind-drilled over a length of three metres. This design eliminated all the welds in the neutron flux area.

The primary containment vessel consists of sections machined from alpha Zircaloy-4 bars for the upper area, and beta Zircaloy-4 for the lower area (operating in PWR conditions). The primary containment assembly was re-machined inside and out to guarantee its straightness. Milling was used to create the nozzles on the finished piece.



Photos 4 and 5: Final machining of the primary containment vessel

Feasibility mock-ups in austenitic steel or aluminium were built for all complex machining operations.



Photos 6 and 7: Bottom of primary containment vessel / Central air heat exchanger

Welding

Welding processes

The welding processes chosen for these two components were as follows:

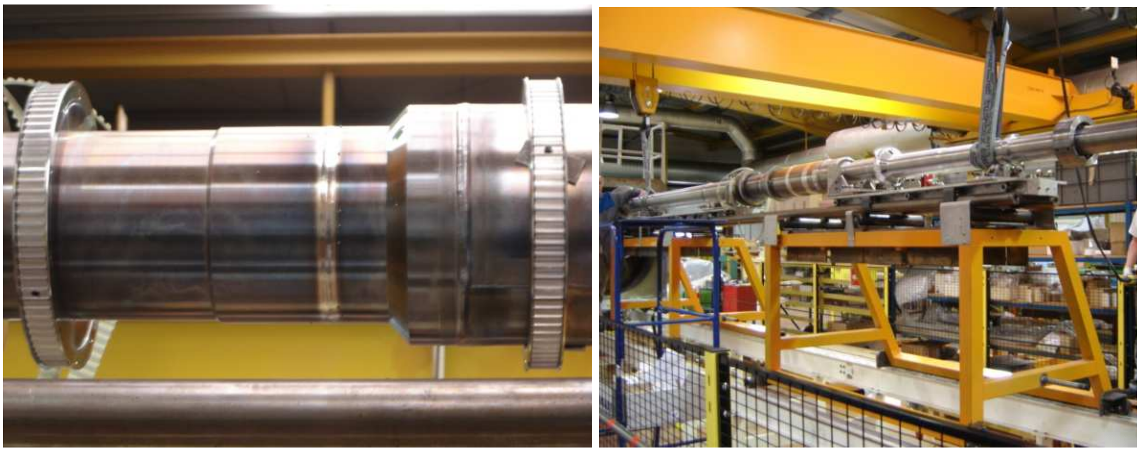
- Pressure vessel:
    - Electron Beam (EB) welding with temporary backing strip,
    - Double Flux TIG with ZR-4 filler metal for the heat exchanger,
    - TIG (butt and socket) welding with ZR-4 filler metal for pipes;
- Safety tube:
    - Plasma welding with ZR-4 filler metal for longitudinal welds,
    - Plasma or TIG welding with ZR 4 filler metal for circular welds.

Electron beam welding (EB)

EB welding was chosen for the thick circular welds (17.5 mm and 23.2 mm) on machined pieces. The use of a backing strip provided support for the molten pool and ensured that the sections to be welded were correctly aligned. This automated vacuum welding process is well adapted to Zircaloy. Gas pollution (notably oxygen) from the molten pool is a major problem in Zircaloy welding and has a highly detrimental effect on the mechanical properties.

Before welding:

After welding:



Photos 8 to 11: Electron Beam welding

Plasma welding

Multi-pass plasma welding with ZR-4 filler metal was chosen to weld the sheet metal components (safety tube shells). In spite of the quality obtained on the formed-welded shells, the slightest fit-up defect (out-of-round, gap) was incompatible with the EB process. As with all of the processes, protecting the molten pool properly from gas pollution is crucial. In plasma welding (as well as TIG welding), such protection is provided by an inert chamber. The inerting quality is guaranteed through oxygen measurements.

Photos 12 to 13: Plasma welds (external, entire assembly, internal)

Photo 14: TIG welding of nozzles

TIG welding

TIG welding with ZR-4 filler metal was chosen for the butt welds and socket-welded nozzles on the primary containment vessel pipe system and for the exchanger plate welds.

Feasibility mock-ups were built to test the welding conditions (accessibility, inerting, etc.) for nozzle welds at the base of the primary containment and exchanger plate welds.

Qualification of welding procedures

Qualification of welding procedures included non-destructive and destructive examinations adapted to the processes. Given the lack of reference frame in that area, detailed specifications for all requirements were drawn up for the different qualification procedures.

Destructive tests

Destructive tests (DT) performed on qualification welds (whatever the welding process) included the following:

- Prismatic tensile test (full-thickness and cross-weld) at ambient temperature;
- Cylindrical tensile test (Φ 10 mm) at high temperature:
  - 200°C for the safety tube qualification procedure,
  - 300°C for the primary containment vessel qualification,
- Bending tests (Face, Root and Side bends),
- Metallographic examination (macrograph and micrographs x200) with a hardness survey on the macrograph,
- Impact strength tests (Charpy V).

The tests on arc weld (TIG and plasma) were supplemented by chemical analysis of the molten zone (test for O, H, N) and corrosion tests according to ASTM G2 to reveal any welding-gas pollution, which would indicate inerting failure.

Non-destructive examinations

The non-destructive examinations (NDE) on the qualification welds were identical to the production weld tests:

- Pre-welding:

    - Visual examination, liquid penetrant tests of the bevels before fit-up. The dye penetrant tests on the EB-welded bevels were replaced by a thorough visual inspection (magnification x5, at 0 and 90°, plus a survey x10 of any signs),
    - Geometric examination of fit-up before welding;
- Post-welding:
    - The following surface tests: visual inspection and dye penetrant tests, where possible on both faces,
    - Radiographic examination.

To guard against any incomplete fusion notch effects, NDE on the primary containment vessel's EB welds were supplemented by the following tests:

- Closed-circuit TV (camera x 24) surface inspection of the root,
- Ultrasonic inspection of compactness with a focus on an incomplete fusion defect at the root,

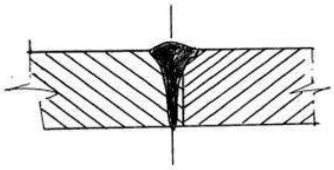


Figure 9: Incomplete fusion at the root

Acceptance of equipment

During the acceptance process, equipments were subjected to the following inspections:

- Dimensional, including a trial insertion of the primary containment vessel into the safety tube,
- Hydraulic tests:
    - 40 bar at ambient temperature for the safety tube,
    - 285 bar at 50°C for the primary containment vessel,
- Helium leak test (after hydraulic test).

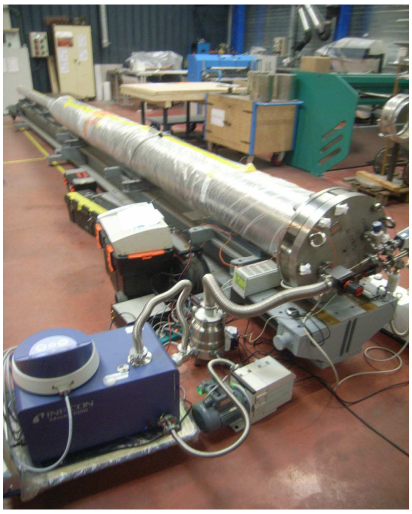


Photo 15: Safety tube helium test

PRIMARY CONTAINMENT VESSEL – INITIAL VISIT/POINT 0

Context

Nuclear pressure equipments installed on the Cabri pressurised water loop are subject to the monitoring and maintenance regulations enforced by the 2005 Nuclear Pressure Equipment French Order. Because it was not possible to fully comply with the monitoring conditions demanded by these regulations, requests for certain arrangements were introduced to the French Nuclear Safety Authority, (ASN).

One of the requests concerned exemption from the periodic visual inspection (every 40 months at the minimum) of all outer surfaces of the primary containment vessel. To compensate for the exemption, the CEA developed ultrasonic and video inspection equipment designed to verify the soundness of the primary containment vessel's six welds and core zone. The main difficulty was implementing the inspections from a distance of more than eight metres in a diameter of only 71 mm.

Equipment functions

The ultrasonic and video equipment serve to:

- Detect interior or exterior longitudinal or circumferential indications at least 10 mm long and 1 mm deep, and characterise the indications starting at 2 mm in depth. This exploration for defects is done using the Time-Of-Flight Diffraction (TOFD) ultrasonic inspection method,
- Determine the primary containment vessel's potential geometric variations by measuring its inner diameter and thickness. The pulse-echo ultrasonic inspection method is used for these precision measurements, which are accurate to +/- 0.1 mm,
- Carry out a televisual inspection of the primary containment vessel interior.

General description of the equipment

The equipment consists of a glove box containing a linear vertical displacement system.

To perform all the measurements, six poles are assembled so as to reach a depth of -8,750 mm.

At the end of these poles there is a centring component (carrier) designed to carry , one after the other, three types of control heads for specific types of measurements.

The carrier also includes a system for rotating the control heads.

During the measurements, the heads move upwards, always turning in the same direction to compensate any mechanical gaps.

Photo 16: Glove box for in-service inspection

Equipment development program

The development program was conducted in three phases.

The first phase involved studying the ultrasonic parameters for Zircaloy and determining the optimal parameters (probe frequency and diameter, angle of refraction in Zircaloy 4, probe centre separation) to detect and characterise longitudinal and transverse defects.

The second phase consisted in validating, on calibration blocks the capacities of: detecting and characterising electro-eroded notches and measuring the thickness and diameter.

During the third phase, full ultrasonic and televisual inspection cycles were performed automatically with the ultrasonic equipment in his final configuration, on a template representing the primary containment vessel (excluding material).

Onsite reference point inspection on the primary containment vessel

The reference point inspection on the primary containment vessel was carried out in December 2009. A video cycle and three ultrasonic cycles were carried out in a row in accordance with the methodology and procedures that were validated during the development phase. The ultrasonic measurements and data acquisitions were performed in the presence of a Cofrend 3 controller to validate acquisitions in real time.

Visual inspection of the primary containment vessel showed no singularities on its inner surface.

TOFD ultrasonic examinations of the welds and core area showed no longitudinal or transverse defects on the primary containment vessel's inner or outer surfaces.

Measurements of the thickness and diameter were consistent with the information from the primary containment vessel fabrication process. This phase served as a point of reference for in-service monitoring of the equipment.

FEEDBACK

There were no nuclear design and construction rules on Zircaloy at the time the Cabri project was launched. To deal with the practical problems encountered in the design and construction, the Cabri project developed a reference system adapted to Zircaloy based on the RCC-M code. As the RCC-MX rules were being drafted at the same time, communication between the teams made it possible to pool industrial experience with the codification process and to integrate some of the feedback. One notable technical aspect is the integration of industrial feedback on welding, forming and inspection procedures.

Exploiting the material data from the tests carried out to support the project confirms the validity of the values used in the RCC-MX Code*. For the tensile properties, a considerable margin between the lowest tensile-strength values measured and the minimum curve for the RCC-MX Code* in the 20°C-200°C range was observed. There is a potential for gain in this range, as the tensile strength is used to determine the permissible stress.

CONCLUSION

The use of Zircaloy to make the pressure equipment for the Cabri project demanded considerable financial, technical and human resources in order to guarantee the high level of quality that is required for nuclear pressure equipment.

Establishing a specific set of rules for the project made it possible to capitalize most of the work done. Integration of industrial experience into the RCC-MX Code* has been mostly completed.

In parallel with the industrial processes, the large number of mechanical characterisation studies on Zircaloy helped validate the design basis data. This major work is now being used to consolidate the minimum curves used in the Code in relation to the considerable statistical data that exists.

We would like to thank all those from IRSN, CEA and AREVA who contributed to this project, as well as other manufacturers who were largely involved.

** A new Afcen code resulting from the merging of RCC-MX in RCC-MR has been drafted during the years 2009 and 2010 (French and English version). The first public release of RCC-MRx 2011 edition is scheduled to be published by Afcen at the end of 2011 or 2012.*