Mol, september, 1 1988
FCP/VEN/01

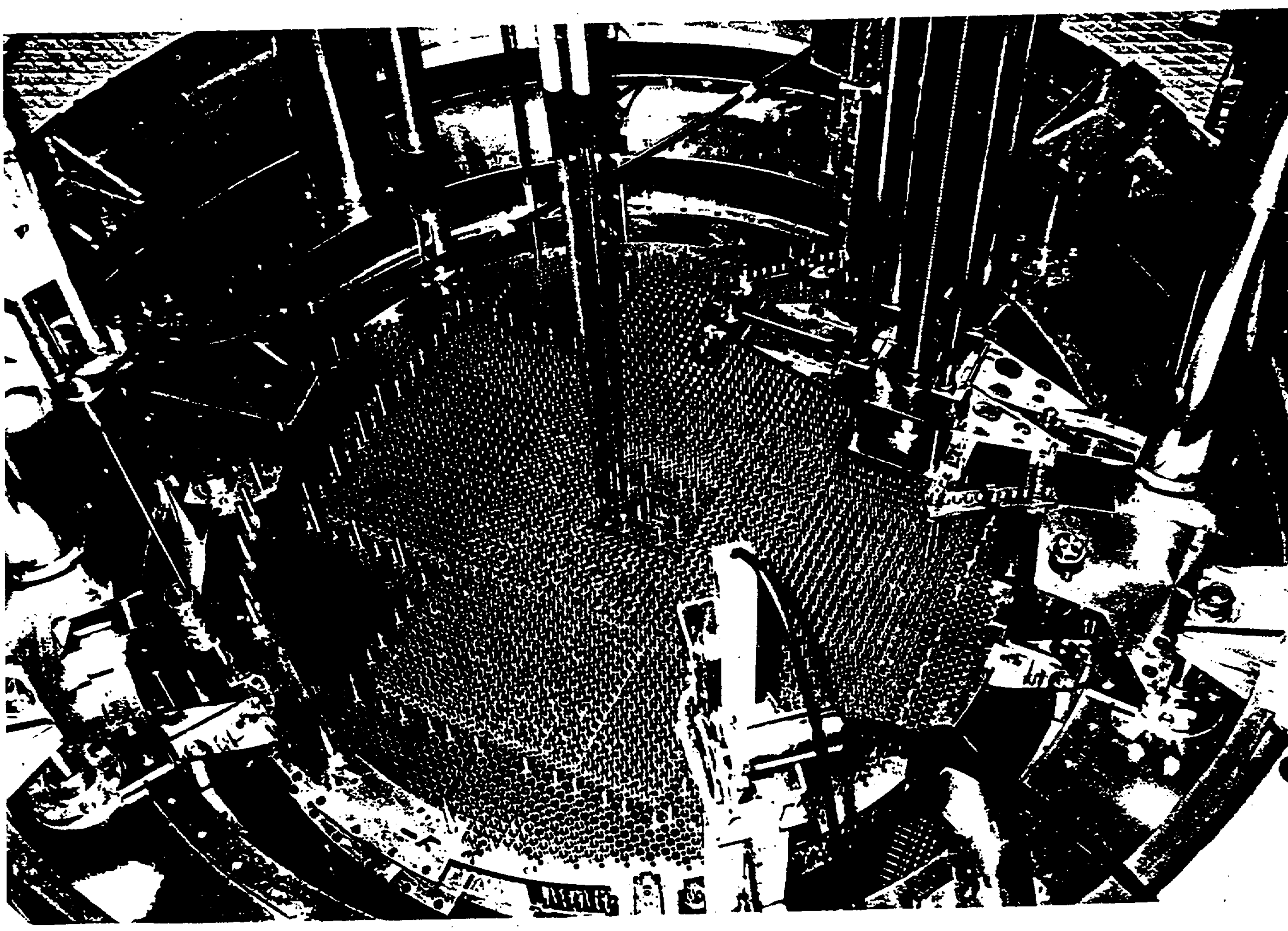
- RESTRICTED DISTRIBUTION -

# LWR-PVS BENCHMARK EXPERIMENT VENUS-3

(with Partial Length Shielded Assemblies)

Core description and qualification

**L. LEENDERS**



S.C.K./C.E.N.
NUCLEAR RESEARCH DEPARTMENT
LL/gd
380/88-13

Mol, September 1, 1988
FCP/VEN/01
File 61.B3235.2214

# LWR-PV BENCHMARK EXPERIMENT VENUS-3
## (with Partial Length Shielded Assemblies)

## 1. Core description and qualification

L. LEENDERS

## FOREWORD

The work described in the present report is carried out in the framework of a cooperation agreement between the National Regulation Committee of the United States and the Centre d'Etudes Nucléaires/Studiecentrum voor Kernenergie of Belgium.
The work carried out in Belgium is sponsored by ELECTRONUCLEAIRE.

As part of the Light Water Reactor - Pressure Vessel Surveillance Dosimetry Improvement Program of the NRC, the VENUS Critical Facility provides Benchmark experiments with a view to improving the PV Lead Factor and/or to improving its prediction, taking Azimuthal and Vertical neutron source contributions into account.

## 1.1. General

The VENUS Critical Facility is a zero power reactor located at CEN/SCK, Mol (Belgium).
This facility was built in 1963-1964, as a nuclear mock-up of a projected marine reactor so-called VULCAIN; hence the name VENUS which means "VULCAIN EXPERIMENTAL NUCLEAR STUDY".

In 1967, this facility was adapted and improved in order to study LWR core designs and to provide experimental data for nuclear code validation. A great flexibility was looked for, as well as an easy handling of the fuel pins, handled one by one, while a great precision of the results had to be achieved.

In 1980, additional material was purchased with a view to studying typical 17x17 PWR fuel assemblies. Such an adaptation is easy : only new reactor grids and small devices adapted to the new fuel geometry are necessary.

In 1982, special stainless steel pieces have been manufactured in order to built a mock-up of the pressure vessel internals representative of a 3 Loop WESTINGHOUSE Power Plant. These stainless steel pieces were delivered at the beginning of December 1982.

Since this date, the facility has been used for three LWR-PVS-Benchmark experiments as follows :

VENUS-1 : This mock-up was aimed to check the calculation procedure for a standard LWR-core, i.e. with fresh $UO_2$ fuel assemblies at the periphery.
The VENUS-1 core was made critical for the first time on December 20, 1982.
The experimental programme was carried out from January 26th, 1983 till June 6th, 1986.

VENUS-2 : Between the possible solutions to reduce the Lead Factor at the PV, it is proposed to replace some fresh $UO_2$ fuel assemblies by burnt fuel assemblies at the most critical corners of the core periphery.

For Benchmark purposes, the VENUS-2 core was obtained by replacing the peripheral $UO_2$ fuel by a MOX fuel, actually simulating a 2 cycle-burnt $UO_2$ fuel (except for FP poisoning). The VENUS-2 core was made critical for the first time on September 16th, 1986.

The corresponding experimental programme was carried out from October 6th, 1986 till December 16th, 1987.

VENUS-3 : For some early built reactors, it is proposed to reduce the Lead Factor at the level of the PV horizontal welding by loading Partial Length Shielded Assemblies at the most critical corners of the core periphery (the shielded part is obtained by replacing part of the fuel length by a stainless steel rod).

For benchmarking this improvement, the VENUS-3 core has been built with 3/0-SS rods at the periphery (the 3/0-SS rods are made of half a length of stainless steel and half a length of 3.3 % $^{235}U$ enriched $UO_2$ fuel).

The VENUS-3 core was made critical for the first time on March 16th, 1988.

The experimental programme started on march 29th, 1988 and is planned to go on until the end of December 1988.

## 1.2. Description of the facility

The facility comprises a reactor shielded room and several associated facilities : the control room, the fuel room, the fuel storage, the gamma scanning device, the counting room and the plutonium laboratory.

The shielded room is partly illustrated on Fig.1.1; under the floor, it contains :

1. The reactor vessel (~ 2.6 $m^3$).
2. The reactor grids (1 m diameter).
3. The safety neutron detectors.
4. The safety system (moderator fast dump).
5. The water- and compressed air-circuitries (not shown in the figure).

The working room (6, above the floor) gives a direct access to the reactor core for loading and unloading fuel pins or experimental thimbles. This room contains :

. the start-up neutron source.
. the reactor- and health physics-controls.
. the regulating rod- or fission chamber-mechanisms.
. and the handling tools.

Due to the direct access to the fuel, the reactor is shutdown when the shielded room is open. The neutron flux level in operation is limited to $10^9$ nv, with a view to limiting the irradiation level of the core and the radioactivity of unloaded fuel pins.

## 1.3. Core design

The LWR-PVS-BENCHMARK experiment in VENUS is aimed at validating the analytical methods needed to predict the azimuthal variation of the fluence in the pressure vessel. The VENUS core was designed with the following objectives :

a) it had to be representative of typical irradiation conditions of a modern PWR vessel :
from exploratory calculations [Ref.1.1.], it appeared that a 3 Loop WESTINGHOUSE plant presents a higher azimuthal gradient of the fluence; this gradient has moreover a higher sensitivity to fuel pattern modification. For this reason, the VENUS mock-up had preferably to simulate the corner assembly environment of such a plant, i.e.

| | | |
|---|---|---|
| - Core baffle thickness | : | 2.858 cm. |
| - Reflector minimum thickness | : | 2.169 cm. |
| - Core barrel thickness | : | 5.161 cm. |
| - First water gap thickness | : | 5.952 cm. |
| - Thermal shield thickness | : | 6.825 cm. |
| - Second water gap thickness | : | 11.431 cm. |
| - Pressure vessel thickness | : | 20.003 cm. |

b) it had fit the grid- and the vessel-geometries of VENUS :
this led to a limitation of the core size and of the amount of simulated internals. In fact :
- the core is made of 16 "15x15" subassemblies, instead of "17x17" ones (the pin-to-pin pitch remains typical of the "17x17" subassembly).
- the second water gap and the pressure vessel are not simulated; a validation of the calculation up to the thermal shield was considered as acceptable; the complete simulation in the radial direction was indeed investigated in a slab geometry with the PCA mock-up.
- except for the baffle- and the reflector minimum-thickness, the thicknesses have been somewhat reduced to fit the VENUS geometry.

c) the core size being defined by a and b, the core loading was adjusted on the basis of preliminary calculations [Ref.1.2. and 1.3] with the following objectives :
- a pure uranium core was preferred as being simpler both experimentally and analytically [Ref.1.4];
- the gamma-heating experiments had to be performed with a low boron content, thus preferably without boron poisoning of the water [Ref.1];
- the radial power shape factor had to be as low as possible, in order to reach, in the different stainless steel pieces, fast flux levels high enough to perform accurate measurements;
- the azimuthal flux variations had to be as high a possible to allow a valuable test of the analytical methods;
- the PLSA-benchmark had to be "representative" despite the significant scaling entailed by the smaller size of VENUS; by "representative" it is meant that an adequate testing is provided for all the sensitive aspects in a discrete-ordinates three dimensional synthesis and superposition approach to an actual PWR/PLSA geometry;
- finally, a quadrangular symmetry was desirable, each quadrant including both the PLSA fuel region and the unperturbed Reference fuel region (for a full flux distorsion and for an accurate calculation/experiment comparison).

All these objectives were attained with the actual core configuration as given in Fig.1.2.

Note : some mechanized absorbing rods, added far from the region of interest, help to adjust the reactivity balance from run to run.

d) preliminary calculations, carried out for VENUS-1, were useful to choose the measurement locations of interest. The 21° and 45° angles, which correspond to the maximum - and minimum fast fluxes respectively, were provided with experimental holes. In particular, access holes are accomodated at 21° and at the centre with a view to performing neutron- and gamma-spectrometry.

Notes : - the angular shape of the core barrel is such that both quadrant and octogonal symmetries are achieved with acceptable reflecting conditions (in stainless steel) at 0°, 45° and 90° respectively.

- the angular shape of the thermal shield, so-called Neutron Pad was limited by the available space (it is moreover removable); the quadrant and octogonal symmetries are also achieved with reflecting conditions in water at 0° and 90° and with reflecting conditions in stainless at 45°. This geometry was moreover considered as representative of some BABCOCK & WILCOX designs.

## 1.4. Core description

Fig.1.2 gives an horizontal cross-section and Fig.1.3 a top view of the actual core. For experimental and analytical purposes, it should be regarded as a perfect symmetrical core reproducing four times the quadrant between 0° and 90°. The other quadrants are loaded with fuel pins "quasi" identical to the fuel pins of the first quadrant (due to fuel inventory limitations) and with some absorbing rods for critically balance adjustment.

Starting from the centre, the core may be divided in 10 horizontal regions :

- the CENTRAL HOLE (water).
- the INNER BAFFLE (stainless steel : 2.858 cm thick).

- the 4/0 FUEL REGION, this region contains stainless steel clad $UO_2$ rods, with 4 % enriched uranium, the rods are typical of a "15x15" lattice (first generation of WESTINGHOUSE plants), they are loaded with the pin-to-pin pitch typical of the "17x17" lattice. 11 PYREX-rods, typical of PWR poison clusters are loaded per quadrant.
- the 3/0 FUEL REGION, this region contains zircaloy clad $UO_2$ rods, with 3.3 % enriched uranium, in a "17x17" lattice; part of this region contents the PLSA rods.
- the OUTER BAFFLE (stainless steel : 2.858 cm thick).
- the REFLECTOR (minimum thickness : 2.169 cm).
- the BARREL (stainless steel : 4.99 cm thick).
- the WATER GAP (water : 5.80 cm thick).
- the NEUTRON PAD (stainless steel, average thickness : 6.72 cm).
- the VENUS environment, i.e. the Jacket (air filled), the Reactor Vessel (stainless steel) and the Reactor Room (air).

Fig.1.4 shows a vertical cross-section of the core. Vertically the core may be divided, from bottom to top, as follows :

- The VENUS room environment (air).
- The LOWER FILLING (water).
- The REACTOR SUPPORT (water and stainless steel).
- The BOTTOM GRID (mainly stainless steel).
- The LOWER REFLECTOR (mainly water and plexiglass); the reflector composition changes a little bit from fuel region to another.
- The ACTIVE HEIGHT (fuel or stainless steel).
- The UPPER REFLECTOR (mainly water and plexiglass), including the INTERMEDIATE GRID (mainly plexiglass).
- the UPPER GRID (mainly stainless steel).
- the UPPER FILLING (water and stainless steel).
- the VENUS room environment (air).

The figure shows clearly that, whatever the region is, the material of interest (i.e. fuel or stainless steel) is located from level 105 cm to level 155 cm (50 cm length). To ensure proper axial buckling conditions, both lower and upper axial reflectors are "quasi" infinite for all the regions (the effective extrapolation length is ~ 7 cm); where necessary water is replaced by plexiglass.

These details could be important for the three-dimensional analytical model.

## 1.5. Qualified data on the core materials

- The core materials are qualified in several ways. For the stainless steels, for instance, the qualification is based on a comparison between the corresponding standard, the certificate delivered by the supplier and, at least, one analysis carried out by CEN/SCK. The adopted value is generally the average of the consistent data (if necessary a weighted average is made) and the given error is the range defined by the extreme values ($\varepsilon = \pm \frac{\text{Max.} - \text{Min.}}{2}$).
- For most of the materials, there is at least one more sample for documentation or later cross-check.
- For the fuel cladding- and the Pyrex-tubes, the linear specific weight has been determined instead of the volume specific weight as the accuracy of checking the tube thickness is too small.
- The impurities of water were checked in the worst conditions, i.e. when the water resistivity reached its lowest value (450 kΩcm); the water temperature is the median value for the experimental period (from 18.03.88 to 29.03.88) and the range is defined by the extreme recorded values.
- For the VENUS internals being outside the LWR-PVS-BENCHMARK mock-up, no qualification was made so that average stainless steel characteristics are given.

The detailed qualification is given in work documents available at CEN/SCK, the results are as follows :

### 1.5.1. CENTRAL HOLE

#### 1.5.1.1. Water composition :

$H_2O$, impurities lower than given here after :

- Diluted oxygen : 0 8.6 ppm (saturation for air-water contact)

| | | | |
|---|---|---|---|
| - Detected impurities : | B | 12 | ppb ($10^{-9}$ g/l) ~ ppm (weight) |
| | Si | 46 | |
| | Mn | 2.5 | |
| | Fe | .7 | |
| | Mg | 5 | |
| | Cu | 5 | |
| | Ca | 75 | |
| | Al | 8 | |
| | Sr | .5 | |
| | Zn | 25 | |
| | V | 5 | |
| | Ag | 2 | |
| | Ba | 15 | |

- Non-detected impurities : Li, Zr, Ti, Be, Nb, Ga, Hf, Co, In, Bi, Ni, Pb, Cd, Te, P, Ge, W, Sb, Cr, Mo, Hg, As, Tl, Sn.

1.5.1.2. Water temperature (24.0 ± 2.0°C)

1.5.2. INNER BAFFLE

1.5.2.1. Chemical composition :

AISI 304 stainless steel

| | |
|---|---|
| C | ( .059 ± .020) W/o |
| Mn | ( 1.651 ± .053) |
| P | ( .030 ± .015) |
| S | ( .013 ± .013) |
| Si | ( .285 ± .129) |
| Cr | (16.370 ± .327) |
| Ni | ( 8.720 ± .185) |
| Mo | ( .454 ± .075) |
| Co | ( .138 ± .070) |
| Fe | (72.281 ± .231) |
| Check | 100.001 |

Detected impurities : - < 10 ppm : Cd, Ta, Au, B
- < 100 ppm : Sm, Eu, Dy, Ir, Gd

Non-detected impurity : Cu

1.5.2.2. Specific weight : (7.902 ± .002) g . $cm^{-3}$

1.5.2.3. Bottom support : Plexiglass (material not qualified)

1.5.3. 3/0 FUEL PIN (standard VENUS fuel pins)

1.5.3.1. Fuel composition : $UO_2$

1.5.3.2. Fuel stoichiometry [O/U] : 1.997 ± .005

1.5.3.3. Fuel isotopic composition of U :

| | |
|---|---|
| $^{234}U$ | ( .029 ± .001) W/o |
| $^{235}U$ | ( 3.306 ± .010) |
| $^{236}U$ | ( .016 ± .001) |
| $^{238}U$ | (96.649 ± .012) |
| Check | 100.000 |

Total impurities : .8 ppm B equivalent in U.

1.5.3.4. Fuel linear specific weight : (5.40 ± .05) $g.cm^{-1}$

1.5.3.5. Fuel diameter : (.819 ± .002) cm

1.5.3.6. Fuel pellet length : (.992 ± .040)

1.5.3.7. Fuel length : (50.0 ± .1) cm

1.5.3.8. Cladding composition : zircaloy 4

| | |
|---|---|
| Sn | (1.41 ± .06) W/o |
| Fe | ( .020 ± .01) |
| Cr | ( .10 ± .01) |
| O | ( .12 ± .01) |
| Zr | (98.17 ± .06) |
| Check | 100.00 |

Detected impurities :
- < 1 ppm : B, Cd, U
- < 10 ppm : Cl, Co, Cu, H, Mg, Mn, Ti, Zn
- < 50 ppm : Al, Hf, N, Nb, Ni, V, W, Au, Ir, Mo, Pb
- < 100 ppm : Ta, Si, Sm, Eu, Dy, Gd, Lu
- 146 ppm : C

1.5.3.9. Cladding linear specific weight : (1.0627 ± .0004) $g.cm^{-1}$

1.5.3.10. Cladding outer diameter : (.950 ± .001) cm

1.5.3.11. Cladding inner diameter : (.836 ± .001) cm

1.5.3.12. Cell pitch : (1.260 ± .001) cm

1.5.3.13. Moderator : water see par.1.5.1.

1.5.3.14. Bottom & top blanket composition : AISI 304 stainless steel

| | | |
|---|---|---|
| C | .042 | W/o |
| Mn | 1.580 | |
| P | .025 | |
| S | .028 | |
| Si | .460 | |
| Cr | 18.200 | |
| Ni | 8.600 | |
| Mo | - | |
| Co | .120 | |
| Fe | 70.945 | (complement to 100) |

Impurities : not available

1.5.3.15. Bottom & top blanket linear specific weight : 4.14 $g.cm^{-1}$

1.5.3.16. Bottom & top blanket diameter : (.820 ± .805) cm

1.5.3.17. Bottom & top blanket length : (.50 ± .01) cm

1.5.3.18. Bottom reflector composition : Plexiglass (not qualified)

1.5.3.19. Bottom reflector linear specific weight : .627 $g.cm^{-1}$

1.5.3.20. Bottom reflector diameter : (.820 ± .805) cm

1.5.3.21. Bottom reflector length : (8.0 ± .01) cm

1.5.3.22. Top reflector composition : Plexiglass (not qualified)

1.5.3.23. Top reflector linear specific weight : .587 $g.cm^{-1}$

1.5.3.24. Top reflector diameter : (.820 ± .805)

1.5.3.24. Top reflector length : (7.57 ± .01) cm

Note : the top reflector is filling the intermediate reactor grid over 1.5 cm of its length.

1.5.3.25. Bottom stop composition : - upper part : Zircaloy 4
- lower part : AISI304

Zircaloy 4 composition : Sn (1.51 ± .03) W/o
Fe ( .22 ± .01)
Cr ( .12 ± .01)
O ( .13 ± .01)
Zr 98.02 (complement to 100)

Detected impurities : - < 1 ppm : B, Cd, Mg, U
- < 10 ppm : Cl, Co, Cu, H, Mn, Zn
- < 50 ppm : Al, Mo, N, Nb, Ni, Pb, Si, Ti, V, W
- < 100 ppm : Hf, Ta
- 82 ppm : C

AISI304 composition : see 1.5.3.14

1.5.3.27. Bottom stop linear specific weight :
- upper part : 3.49 $g.cm^{-1}$
- lower part : 5.58 $g.cm^{-1}$

1.5.3.28. Bottom stop diameter : .950 cm

1.5.3.29. Bottom stop length : - upper part : 1.25 cm
- lower part : .90 cm

1.5.3.30. Top stop composition : AISI 304 stainless steel (see 1.5.3.14)

1.5.3.31. Top stop linear specific weight : 5.64 $g.cm^{-1}$

1.5.3.32. Top stop diameter : .950 cm

1.5.3.33. Top stop length : 2.23 cm

Note : the top stop is assumed to end with the upper face of the upper reactor grid, the highest 1.45 cm of this stop is filling the hole of the upper reactor grid.

1.5.4. PYREX PIN

1.5.4.1. Pyrex composition : Corning glass code 7740

| | | |
|---|---|---|
| $SiO_2$ | 78.53 | W/o |
| $B_2O_3$ | (14.65 $\pm$ .15) | |
| $Al_2O_3$ | 2.21 | |
| $Fe_2O_3$ | .05 | |
| $Na_2O$ | 3.44 | |
| $K_2O$ | 1.13 | |
| Check | 100.01 | |

1.5.4.2. Isotopic composition of B : $^{10}B$ : (19.775 $\pm$ .005) At %
$^{11}B$ : (80.225 $\pm$ .005)

1.5.4.3. Pyrex outer diameter : (.9048 $\pm$ .0043) cm

1.5.4.4. Pyrex inner diameter : (.6058 $\pm$ .0031) cm

1.5.4.5. Pyrex linear specific weight : (.7886 $\pm$ .0052) $g.cm^{-1}$

1.5.4.6. Cladding composition : AISI 304 stainless steel

| | | |
|---|---|---|
| C | ( .03 $\pm$ .03) | W/o |
| Mn | ( .87 $\pm$ .42) | |
| Si | ( .29 $\pm$ .16) | |
| Cr | (18.40 $\pm$ .10) | |

Ni ( 9.50 ± .50)

Mo ( .07 ± .07)

Fe (70.84 ± 1.28)

Check 100.00

<u>1.5.4.7. Cladding specific weight</u> : (7.9 ± .1) g.cm$^{-3}$

<u>1.5.4.8. Cladding outer diameter</u> : (.978 ± .005) cm

<u>1.5.4.9. Cladding inner diameter</u> : (.940 ± .003) cm

<u>1.5.4.10. Cell pitch</u> : (1.260 ± .001) cm

<u>1.5.4.11. Moderator</u> : water see par.1.5.1.

<u>1.5.4.12. Bottom & top blanket composition : Aluminium</u>
(purity : 99.5 % Al, not qualified)

<u>1.5.4.13. Bottom & top blanket linear specific weight</u> : 1.83 g.cm$^{-1}$

<u>1.5.4.14. Bottom & top blanket diameter</u> : (.930 ± .805) cm

<u>1.5.4.15. Bottom & top blanket length</u> : (.50 ± .01) cm

<u>1.5.4.16. Bottom reflector composition</u> : Plexiglass (not qualified)

<u>1.5.4.17. Bottom reflector linear specific weight</u> : .806 g.cm$^{-1}$

<u>1.5.4.18. Bottom reflector diameter</u> : (.930 ± .805) cm

<u>1.5.4.19. Bottom reflector length</u> : (8.00 ± .01) cm

<u>1.5.4.20. Top reflector composition</u> : Plexiglass (not qualified)

<u>1.5.4.21. Top reflector linear specific weight</u> : .769 g.cm$^{-1}$

<u>1.5.4.22. Top reflector diameter</u> : (.930 ± .805) cm

1.5.4.23. Top reflector length : (7.57 ± .01) cm

Note : the top reflector is filling the intermediate reactor grid over 1.5 cm of its length.

1.5.4.24. Bottom stop composition : AISI 304 stainless steel

1.5.4.25. Bottom stop linear specific weight : 5.03 $g.cm^{-1}$ (estimated)

1.5.4.26. Bottom stop diameter : .978 cm

1.5.4.27. Bottom stop length : 2.15 cm

1.5.4.28. Top stop composition : AISI 304 stainless steel (not qualified)

1.5.4.29. Top stop linear specific weight : 5.97 $g.cm^{-1}$ (estimated)

1.5.4.30. Top stop diameter : .978 cm

1.5.4.31. Top stop length : 2.23 cm

Note : the top stop is assumed to end with the upper face of the upper reactor grid. The highest 1.45 cm of this stop is filling the upper reactor grid.

1.5.5. 4/0 FUEL PIN (standard VENUS fuel pins, 3rd delivery)

1.5.5.1. Fuel composition : $UO_2$

1.5.5.2. Fuel stoichiometry [O/U] : $2.00 \pm 0.01$

1.5.5.3. Isotopic composition of U : $^{234}U$ ( .031 ± .009) W/o
$^{235}U$ ( 4.022 ± .008)
$^{236}U$ ( .023 ± .006)
$^{238}U$ (95.924 ± .010)

Impurities : not available.

1.5.5.4. Fuel linear specific weight : (6.39 ± .70) $g.cm^{-1}$

1.5.5.5. Fuel diameter : (.8926 ± .0005) cm

1.5.5.6. Fuel Pellet length : (1.114 ± .115) cm

1.5.5.7. Fuel length : (50.0 ± .5) cm

1.5.5.8. Cladding composition : AISI 304 stainless steel

| | |
|---|---|
| C | ( .040 ± .040) W/o |
| Mn | ( 1.290 ± .030) |
| P | ( .020 ± .020) |
| S | ( .015 ± .015) |
| Si | ( .135 ± .003) |
| Cr | (18.300 ± .400) |
| Ni | (10.030 ± .200) |
| Mo | ( .132 ± .003) |
| Fe | (70.038 ± .711) |

Detected impurities : -< 10 ppm : Cd, Ta, Au, B, Co
-< 100 ppm : Sm, Eu, Dy, Ir, Gd

1.5.5.9. Cladding linear specific weight : (.8855 ± .0007) $g.cm^{-1}$

1.5.5.10. Cladding outer diameter : (.978 ± .002) cm

1.5.5.11. Cladding inner diameter : (.902 ± .004) cm

1.5.5.12. Cell pitch : (1.260 ± .001) cm

1.5.5.13. Moderator : water see par.1.5.1.

1.5.5.14. Bottom reflector composition : Plexiglass (not qualified)

1.5.5.15. Bottom reflector linear specific weight : .738 $g.cm^{-1}$

1.5.5.16. Bottom reflector diameter : (.89 $\pm$ .03) cm

1.5.5.17. Bottom reflector length : (8.80 $\pm$ .02) cm

1.5.5.18. Top reflector composition : Plexiglass (not qualified)

1.5.5.19. Top reflector linear specific weight : .738 $g.cm^{-1}$

1.5.5.20. Top reflector diameter : (.89 $\pm$ .03) cm

1.5.5.21. Top reflector length : (7.00 $\pm$ .02) cm

Note : the Top Reflector is filling the intermediate reactor grid over 1.5 cm of its length.

1.5.5.22. Bottom stop composition : AISI 304 L stainless steel (not qualified)

1.5.5.23. Bottom stop linear specific weight : 0.593 $g.cm^{-1}$

1.5.5.24. Bottom stop diameter : 0.978 cm

1.5.5.25. Bottom stop length : 1.85 cm

1.5.5.26. Top stop composition : AISI 304 L stainless steel (not qualified)

1.5.5.27. Top stop linear specific weight : 0.636 $g.cm^{-1}$

1.5.5.28. Top stop diameter : .978 cm

1.5.5.29. Top stop length : 3.3 cm

Note : the top stop is assumed to end with the upper face of the upper reactor grid, the highest 1.45 cm of this stops is filling the upper grid.

1.5.6. OUTER BAFFLE (stainless steel see par.1.5.2.)

1.5.7. REFLECTOR (water see par.1.5.1.)

1.5.8.1. Chemical composition : AISI 304 stainless steel

| | | |
|---|---|---|
| C | .015 | W/o |
| Mn | ( 1.303 ± .430) | |
| P | .028 | |
| S | .005 | |
| Si | .513 | |
| Cr | (18.464 ± .200) | |
| Ni | (10.199 ± .380) | |
| Mo | .474 | |
| Co | .097 | |
| Fe | (68.819 ± 1.010) | |
| N | .080 | |
| Check | 99.997 | |

Not-detected impurities : Cd, Sm, Eu, Dy, Ir, Gd, Ta, Cu, Au, B

1.5.8.2. Specific weight : (7.9 ± .1) $g.cm^{-3}$ (not qualified so far)

1.5.9. WATER GAP (water see par.1.5.1.)

1.5.10. NEUTRON PAD

1.5.10.1 Chemical composition : AISI 304 stainless steel

| | | |
|---|---|---|
| C | .016 | W/o |
| Mn | ( .830 ± .280) | |
| P | .026 | |
| S | .004 | |
| Si | .395 | |
| Cr | (18.022 ± .030) | |
| Ni | (10.588 ± .360) | |
| Mo | .425 | |
| Co | .196 | |
| Fe | (69.498 ± .670) | |
| Check | 100.000 | |

Not-detected impurities : Cd, Sm, Eu, Dy, Ir, Gd, Ta, Cu, Au, B

1.5.10.2. Specific weight : (7.9 ± .1) $g.cm^{-3}$ (not qualified so far)

1.5.11. SPACE BETWEEN NEUTRON PAD AND JACKET (water see par.1.5.1.)

1.5.12. JACKET INNER WALL

1.5.12.1. Chemical composition : AISI 304 stainless steel (not qualified)

| | |
|---|---|
| C | ( .024 ± .012) |
| Mn | ( 1.168 ± .270) |
| P | ( .025 ± .003) |
| S | ( .008 ± .005) |
| Si | ( .374 ± .150) |
| Ce | (17.619 ± 1.047) |
| Ni | ( 9.836 ± .934) |
| Mo | ( .452 ± .024) |
| Co | ( .113 ± .074) |
| Fe | (70.354 ± 1.963) |
| N | ( .027 ± .040) |
| Check | 100.000 |

1.5.12.2. Specific weight : (7.9 ± 1) $g.cm^{-3}$ (not qualified)

1.5.13. JACKET VOLUME (Air with 100 % relative humidity)

1.5.14. JACKET OUTER WALL (stainless steel see par.1.5.12)

1.5.15. SPACE BETWEEN JACKET AND REACTOR VESSEL (water see par.1.5.1)

1.5.16. REACTOR VESSEL WALL (stainless steel see par.1.5.12)

1.5.17. AROUND THE REACTOR VESSEL (Dry air)

1.5.30. SS-3/O PLSA PIN

1.5.30.1 to 13 : Upper 3/O fuel part
same data as 1.5.3.1 to 13, except for 1.5.30.7 (fuel length)

1.5.30.7. Fuel length : (25.00 ± .08) cm

1.5.30.14 to 33 : Blankets, Reflectors and stops
same data as 1.5.3.14 to 33

Note : following items are concerned with the Lower SS-PLSA part

1.5.30.34. SS composition : AISI 304 stainless steel

| | |
|---|---|
| C | ( .024 ± .012) |
| Mn | ( 1.186 ± .160) |
| P | ( .025 ± .003) |
| S | ( .008 ± .005) |
| Si | ( .374 ± .150) |
| Cr | (18.710 ± .120) |
| Ni | ( 9.832 ± .370) |
| Mo | ( .183 ± .020) |
| Co | ( .105 ± .005) |
| Cd | ( .005 ± .005) |
| B | ( .005 ± .005) |
| Fe | (69.538 ± 1.075) |
| Check | 100.000 |

1.5.30.35. SS linear specific weight : (4.138 ± .002) $g.cm^{-1}$

1.5.30.36. SS diameter : (.817 ± .002) cm

1.5.30.37. SS rod length : (25.01 ± .02) cm

1.5.30.38 to 43 : same data as 1.5.3.8 to 13

1.5.18. LOWER FILLING
water, see par.1.5.1.2

1.5.19. BOTTOM SUPPORT

1.5.19.1. Composition : water : 93.36 vol %
stainless steel : 6.64 vol %

1.5.19.2. Water composition : see par.1.5.1.

1.5.19.3. SS composition : AISI 304 not qualified,
see item 1.5.12.1

1.5.20. BOTTOM GRID

1.5.20.1. Composition : water : 32.8 vol %
stainless steel : 67.2 vol %

Note : the bottom pin of the fuel pin is included in the bottom stop, which is assumed to be cylindrical and to be supported by the upper face of the bottom grid.

1.5.20.2. Water composition : see par.1.5.1

1.5.20.3. SS composition : AISI 304 not qualified
see item 1.5.12.1.

1.5.21. LOWER REFLECTOR

The lower reflector is the region defined by the following borders :

a) the upper face of the bottom grid (for the inner part) and the upper face of the reactor support (for the outer part).
b) the fuel bottom and/or the stainless steel piece bottom.
c) the jacket inner wall.

Its composition varies according to the lateral region concerned (I to XI) as follows :

1.5.21.1. Below central hole (I) : water, see par.1.5.1.

1.5.21.2. Below inner baffle (II) : plexiglass (not qualified)

1.5.21.3. Below 4/O fuel (III) : see 4/O fuel pin description,
items 1.5.5.14-17 and 22-25

Below pyrex tube (III) : see pyrex pin description,
items 1.5.4.12-19 and 24-27

1.5.21.4. Below 3/O fuel (IV) : see 3/O fuel pin description,
items 1.5.3.14-21 and 26-29

1.5.21.5. Below PLSA fuel (V) : see SS-3/O PLSA pin description,
items 1.5.30.14-21 and 26-29 equivalent
to 1.5.3.14-21 and 26-29

1.5.21.6. Below outer baffle (VI) : plexiglass (not qualified)

1.5.21.7. Below lateral reflector (VII) : water, see par.1.5.1.

1.5.21.8. Below barrel (VIII) : plexiglass (not qualified)

1.5.21.9. Below water gap (IX) : water, see par.1.5.1.

1.5.21.10. Below neutron pad (X) : water, see par.1.5.1.

1.5.21.11. Below space between Pad and Jacket (XI) :
water, see par.1.5.1.

1.5.22. INTERMEDIATE GRID

1.5.22.1. Composition : water : 63.4 vol %
plexiglass : 36.6 vol %

Note : the intermediate reactor grid is partially filled by the pins, such that water is partially replaced by plexiglass and cladding tube.

1.5.22.2. Water composition : see par.1.5.1.

1.5.22.3. Plexiglass composition : not qualified

1.5.23. UPPER REFLECTOR

The upper reflector is the region defined by the following borders :

a) the fuel top and/or the stainless steel piece top.

b) the lower face of the upper grid.

c) the jacket inner wall.

The reflector composition varies according to the lateral region concerned (I to XI) as follows :

1.5.23.1. Above central hole (I) : water, see par.1.5.1. (1)

1.5.23.2. Above inner baffle (II) : water, see par.1.5.1. (1)

1.5.23.3. Above 4/O fuel (III) : see 4/O fuel pin description, items 1.5.5.18-21 and 26-29 (1)

Above a pyrex tube (III) : see pyrex pin description, items 1.5.4.12-15, 20-23 and 28-31 (1)

1.5.23.4. Above 3/O fuel (IV) : see 3/O fuel pin description, items 1.5.3.14-17, 22-25 and 30-33 (1)

1.5.23.5. Above PLSA fuel (V) : see SS - 3/O PLSA pin description, items 1.5.30.14-17, 22-25 and 30-33 equivalent to 1.5.3.14-17, 22-25 and 30-33 (1)

1.5.23.6. Above outer baffle (VI) : water, see par.1.5.1. (1)

1.5.23.7. Above lateral reflector (VII) : water, see par.1.5.1. (1)

1.5.23.8. Above barrel (VIII) : water, see par.1.5.1.

1.5.23.9. Above water gap (IX) : water, see par.1.5.1.

1.5.23.10. Above neutron pad (X) : water, see par.1.5.1.

1.5.23.11. Above space between Pad and Jacket (XI) : water, par.1.5.1.

Note (1) : take account with the presence of plexiglass in the water at the level of the intermediate reactor grid, as given in par.1.5.22.

1.5.24. UPPER GRID

1.5.24.1. Composition : water : 63.4 vol %
stainless steel : 36.6 vol %

Note : this is the composition where no pin is loaded, in the loaded part the water is partially replaced stainless steel due to the top stop of the pin (regions III, IV and V).

1.5.24.2. Water composition : see par.1.5.1.

1.5.24.3. SS composition : AISI 304 not qualified, see item 1.5.12.1.

1.5.25. UPPER FILLING : water, see par.1.5.1.

## 1.6. Qualified data on the core geometry

The components of the mock-up were qualified in sizes during fabrication and before loading in the core, special attention was paid to the stainless steel thicknesses.
Some data, particularly sensitive for the fast neutron depletion, were checked in the core as built : for instance, the minimum outer Baffle-Barrel distance, the Water Gap thickness and the azimuthal location of the Neutron Pad. All the recorded data were combined to describe the mock-up as given in Fig.1.5. and 1.6. Where no qualification was possible, the data were deduced from the fabrication specifications.

Notes :
- during the mounting, it was stated that the Neutron Pad did not take its designed azimuthal location, probably due to some machining mistake; it has been decided, on site, to adjust the V3 Hole (foreseen at the highest azimuthal fast neutron flux and accommodated for spectrometry) at the angle 21.1°.
- up to the inner diameter of the Neutron Pad, all the components are concentric with respect to the core centre, they are defined by distances or radii d1 to d10, the VENUS internals (Jacket and Reactor Vessel) are concentric with respect to a

point located at X' = -3.15 cm, Y' = -3.15 cm in the core model, as a consequence their locations are no longer given by radii but by thicknesses t9 to t20 and the Neutron Pad has a variable thickness.

- for the active height, the components are 50 cm high and the following data are given : LL = Lower Level, UL = Upper Level, h = height (see Fig.1.4); for other vertical regions, actually located from level 0 to 168 cm, the levels are given from bottom to top (see fig.1.6).

The detailed qualification is given in work documents available at CEN/SCK, the data are as follows :

1.6.1. CENTRAL HOLE (I, fig.1.5 & 1.6)

d1 = (3.442 ± .021) cm

1.6.2. INNER BAFFLE (II, fig.1.5 & 1.6)

| | | |
|---|---|---|
| d2 | = ( 6.300 ± .013) cm | |
| t1 | = ( 2.858 ± .003) cm | |
| LL II | = (104.849 ± .032) cm | (1) |
| UL II | = (154.856 ± .036) cm | (1) |
| h II | = ( 50.006 ± .004) cm | (1) |

1.6.3. 4/O FUEL REGION (III, fig.1.5 & 1.6)

| | | |
|---|---|---|
| d3 | = ( 18.900 ± .005) cm | |
| t2 | = ( 12.600 ± .005) cm | |
| d4 | = ( 26.460 ± .005) cm | |
| t3 | = ( 7.56 ± .005) cm | |
| d11 | = ( 18.900 ± .013) cm | |
| LL III | = (105.00 ± .05) cm | (1) |
| UL III | = (155.00 ± .55) cm | (1) |
| h III | = ( 50.0 ± .5) cm | (1) |

Note (1) : Active height only !

1.6.4. 3/O FUEL REGION (IV, fig.1.5 & 1.6)

d5 = ( 31.500 $\pm$ .005) cm

t4 = ( 5.040 $\pm$ .005) cm

d6 = ( 37.800 $\pm$ .013) cm

t5 = ( 11.34 $\pm$ .014) cm

d11 = ( 18.900 $\pm$ .013) cm

LL IV = (105.00 $\pm$ .05) cm (1)

UL IV = (155.00 $\pm$ .15) cm (1)

h IV = ( 50.0 $\pm$ .1) cm (1)

1.6.5. 3/O - SS FUEL REGION (V, fig.1.5 & 1.6)

d6 = ( 37.800 $\pm$ .013) cm

t6 = ( 6.300 $\pm$ .014) cm

d11 = ( 18.900 $\pm$ .019) cm

LL V = (105.00 $\pm$ .05) cm (Stainless steel bottom) (1)

ML V = (130.01 $\pm$ .07) cm (Border SS-3/O fuel) (1)

UL V = (155.01 $\pm$ .15) cm (3/O fuel top) (1)

h SS-V = ( 25.01 $\pm$ .02) cm (1)

h 3/O-V = ( 25.00 $\pm$ .08) cm

1.6.6. OUTER BAFFLE (VI, fig.1.5 & 1.6)

d7 = ( 40.658 $\pm$ .021) cm

d12 = ( 21.758 $\pm$ .021) cm

t7 = ( 2.858 $\pm$ .003) cm

LL VI = (104.850 $\pm$ .033) cm (1)

UL VI = (154.850 $\pm$ .039) cm (1)

h VI = ( 50.000 $\pm$ .006) cm (1)

1.6.7. REFLECTOR (VII, fig.1.5 par.1.6)

t15 (distance between Baffle corner and Barrel) = (2.169 $\pm$ .080) cm

t15 bis (idem, but taking account of broken corners = (2.251 $\pm$ .080) cm

d8 (Barrel inner radius) = (48.283 $\pm$ 0.050) cm

Note (1) : Active height only !

1.6.8. BARREL (VIII, fig.1.5 & 1.6)

d8 = ( 48.283 ± 0.050) cm

d9 = ( 53.273 ± .060) cm

t8 = ( 4.99 ± .01) cm

LL VIII = (105.00 ± .06) cm (1)

UL VIII = (155.00 ± .16) cm (1)

h VIII = ( 50.0 ± .1 ) cm (1)

1.6.9. WATER GAP (IX, fig.1.5 & 1.6)

t16 = (5.800 ± .060) cm

1.6.10. NEUTRON PAD (X,

d10 = ( 59.073 ± .120) cm

t17 = ( 6.300 ± .030) cm

t18 = ( 6.690 ± .030) cm

t19 = ( 7.050 ± .030) cm

t20 = ( 6.900 ± .030) cm

a1 = ( 11.25 ± .25)° cm

a2 = ( 21.10 ± .10)° cm

a3 = 45°

a4 = ( 54.75 ± .25)°

LL X = (105.00 ± .26) cm (1)

UL X = (155.00 ± .16) cm (1)

h X = ( 50.0 ± .1) cm (1)

1.6.11. SPACE BETWEEN NEUTRON PAD AND JACKET (XI, fig.1.5 & 1.6)

e17 = (.3 ± .3) cm at 11.25°

e18 = (.3 ± .3) cm at 21.10°

e19 = (.332 ± .310) cm at 45°

e20 = (.3 ± .3) cm at 54.75°

1.6.12. JACKET INNER WALL (XII, fig.1.5 & 1.6)

t9 = (11.80 ± .21) cm

t10 = .5 cm

Note : the inner radius of the Jacket Inner Wall is (62.0 ± .15) cm with respect to a centre being at (X' = -3.15 cm, Y' = -3.15 cm) from the core centre, all the next internals are concentric with this Jacket Inner Wall.

Note (1) : Active height only !

1.6.13. JACKET VOLUME (XIII, Fig.1.5 & 1.6)

t11 = (15.0 ± .3) cm

1.6.14. JACKET OUTER WALL (XIV, fig.1.5 & 1.6)

t12 = .5 cm

1.6.16. REACTOR VESSEL WALL (XVI (fig.1.5 & 1.6)

t14 = .4 cm

1.6.17. REACTOR ROOM (XVII fig.1.5 & 1.6)

Infinite medium filled by air.

1.6.18. LOWER FILLING (XVIII, fig.1.6)

h0 = 0 cm

h1 = 83.45 cm

$r_{18}$ = defined by Jacket Inner Wall, see item 1.16.12

1.6.19. REACTOR SUPPORT (XIX, fig.1.6)

h2 = 92.85 cm

t19 = (9.40 ± .05) cm

1.6.20. BOTTOM GRID (XX, fig.1.6)

h3 = 94.35 cm

t20 = (1.50 ± .81) cm

r20 = (50.00 ± .81) cm

Note : the grid centre is at (X' = -3.15 cm, Y' = -3.15 cm) from the core centre.

1.6.21. LOWER REFLECTOR (XXI, fig.1.6)

h4 = 96.20 cm (upper end of bottom stop of 4/0 fuel pins)

h5 = 96.50 cm (upper end of bottom stop of other pins)

h6 = 104.50 cm (lower end of blanket for all the pins, except 4/0 fuel pins)

h7 = 105,0 cm (bottom active height)

r21 = defined by Jacket Inner Wall, see item 1.16.12

1.6.22. INTERMEDIATE GRID (XXII, fig.1.6)

h11 = 156.30 cm

h12 = 157.80 cm

t22 = 1.5 cm

r22 = (50.00 ± .81) cm

Note : the grid centre is at (X' = -3.15 cm, Y' = -3.15 cm) from the core centre.

1.6.23. UPPER REFLECTOR (XXIII, fig.1.6.)

h9 = 155.0 cm (top active height)

h10 = 155.5 cm (upper end of blanket for all the pins, except 4/0 fuel pins)

h13 = 162.0 cm (upper end of reflector in 4/0 fuel pins)

h14 = 163.07 cm (upper end of reflector in other pins)

r23 = defined by Jacket Inner Wall, see item 1.16.12

1.6.24. UPPER REACTOR GRID (XXIV, fig.1.6)

h15 = 163.85 cm

h16 = 165.30 cm

t = ( 1.45 ± .81) cm

r24 = (50.00 ± .01) cm

Note : the grid centre is at (X' = -3.15 cm, Y' = -3.15 cm) from the core centre.

1.6.25. UPPER FILLING (XXV, fig.1.6)

h17 = 168.0 cm (water level)

Note : - h18 is the top of both the Jacket and the Reactor Vessel

h18 = 170.8 cm

- h8 is the mid-plane of the reactor active height.

h8 = 130.0 cm

## 1.7. References

Ref.1.1. LWR Pressure Vessel Surveillance Dosimetry Improvement Program Review Meeting, NBS, Maryland, Oct.26-30, 1981 : Exploratory calculations carried out at WESTINGHOUSE, S. ANDERSON in cooperation with G. GUTHRIE (HEDL).

Ref.1.2. VENUS-3 PLSA Conceptual Design Considerations CEN/SCK Note AF/sa 380/87-02, Feb.2, 1987
A. FABRY

Ref.1.3. Design Studies of VENUS-3, a Benchmark Experiments of PLSA calculational procedures to be performed in the VENUS critical Facility at Mol.

Ref.1.4. LWR Pressure Vessel Surveillance Dosimetry Program "Activities, Status and Scheduling", March 29-April 2, 1982.

## 18. DISTRIBUTION

| | | | |
|---|---|---|---|
| NRC | (USA) | A. TABOADA | |
| | | C.Z. SERPAN | |
| NBS | (USA) | F.D.Mc GARRY | |
| HEDL | (USA) | W.N. Mc ELROY | |
| ORNL | (USA) | F.B.K. KAM | |
| | | R.E. MAERKER | |
| CEN/SCK | (ADM) | H. CEULEMANS | |
| | (LHMA) | A. DEMILDT | |
| | (BR1) | P. D'HONDT | |
| | | A. FABRY | |
| | | L. LEENDERS | (2x) |
| | | G. MINSART | |
| | | L. VERBRUGGEN | |

SECRETARY (BR1) : 6 copies

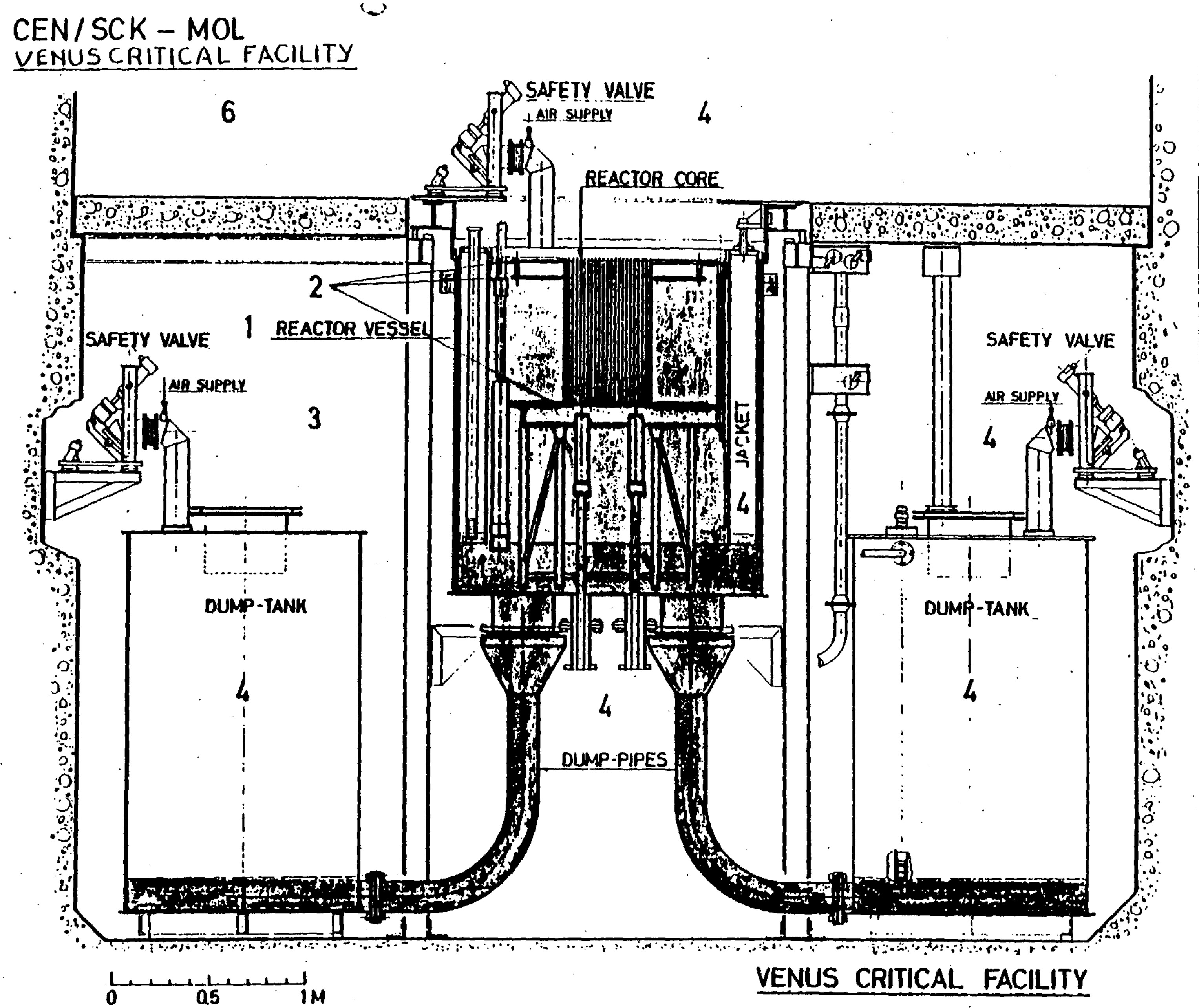



Fig. 1.1 : VERTICAL CROSS-SECTION OF THE FACILITY.

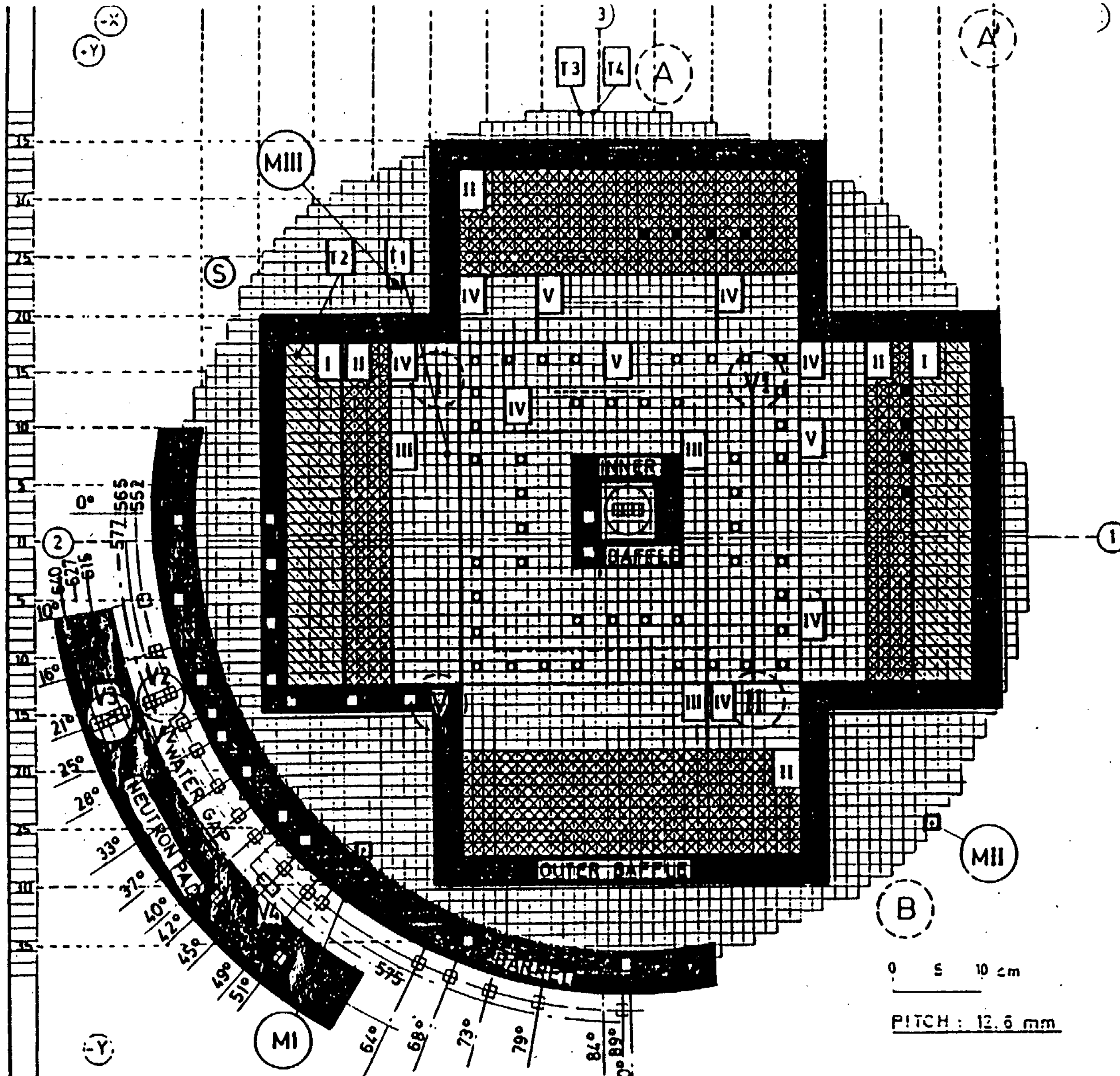



FIG. : SCHEMATIC VIEW OF THE CORE LATTICE

EXPERIMENT : VENUS-3 : LWR-PVS - BENCHMARK (PLSA)

DATE : from 28 03 88 to

CONFIGURATION N° 31 / 08

DENSITY RODS : NONE

BORON CONCENTRATION (p.p.m.): NONE

START-UP SOURCE (S) YES

NEUTRON GENERATOR (N) NONE

ABSORBING ROD ■ 8R Level ~ 3/4 fuel height

PYREX ROD □ 44

FUEL REGIONS · TOTAL :( 2600 - 52 ) PINS

| DESIGNAT. | %U5/%Pu | COLOUR OR SYMBOL | NUMBER OF FUEL PINS | EQ. RADIUS OR X . Y | INVESTIGATED CELL |
|---|---|---|---|---|---|
| I | SS-3/0 | | 300 | | |
| II | 3/0 | | 780 - 8 | | |
| III | 4/0 (3) | | 648 - 17 | | |
| IV | 4/0 (2) | | 456 - 12 | | |
| V | 4/0 (1) | | 416 - 15 | | |

MONITORING DETECTORS :

| DESIGNAT. | | DIAMET. | SYMBOL | N° CABLE | LOCATION x/y | LEVEL | CHANNEL |
|---|---|---|---|---|---|---|---|
| PROPORTIONAL BF3 COUNTER | | | | | | | |
| FISSION CHAMBER | | 1/8" 5U | MI | - | -21 / -27 | Bottom | C |
| | | 1/4" 5U | MII | - | +29 / -25 | Bottom | E |
| | | 1mm 5U | MIII | - | -18 / +23 | Mid. pl. | Nim-rack |

CONTROL DETECTORS

| DESIGNAT. | DIAMET. | SYMBOL | N° | LOCATION | LEVEL | CHANNEL |
|---|---|---|---|---|---|---|
| PROPORTIONAL COUNTER | 1" | (A') | | wall | - | A |
| | 1" | (B) | | 6 | Bottom | B |
| ION CHAMBER (NON-COMPENSATED) | | (I) | | - | under reactor | log I |
| | | (II) | | - | | log II |
| | | (V) | | - | | lin V |
| | | (VI) | | - | | lin VI |

REMARK : $k_{eff}$ = 1 for water at 1680 mm & $R_2$ at ~1400 mm

VERIFIED BY. [signature] APPROVED BY: [signature]

REMARKS : (1) First delivery (2) Second delivery (3) Third delivery

Issued : 28.03.88

88 / B 3235 / 65503

Fig. 1.2. CORE DESCRIPTION (Horizontal Cross-section)

CEN / SCK - MOL

VENUS CRITICAL FACILITY

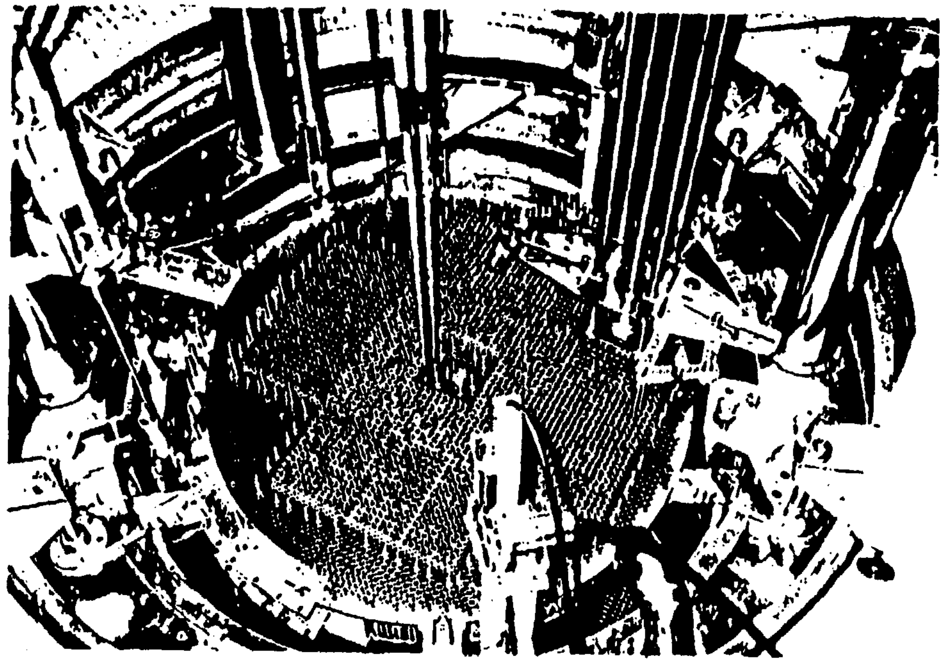


Fig. 1.3 : TOP VIEW OF THE VENUS CORE WITH THE LWR-PVS-BENCHMARK EXPERIMENT.

88/B3235/6508B

VENUS CRITICAL FACILITY LWR PVS BENCHMARK : VENUS-3 (PLSA)

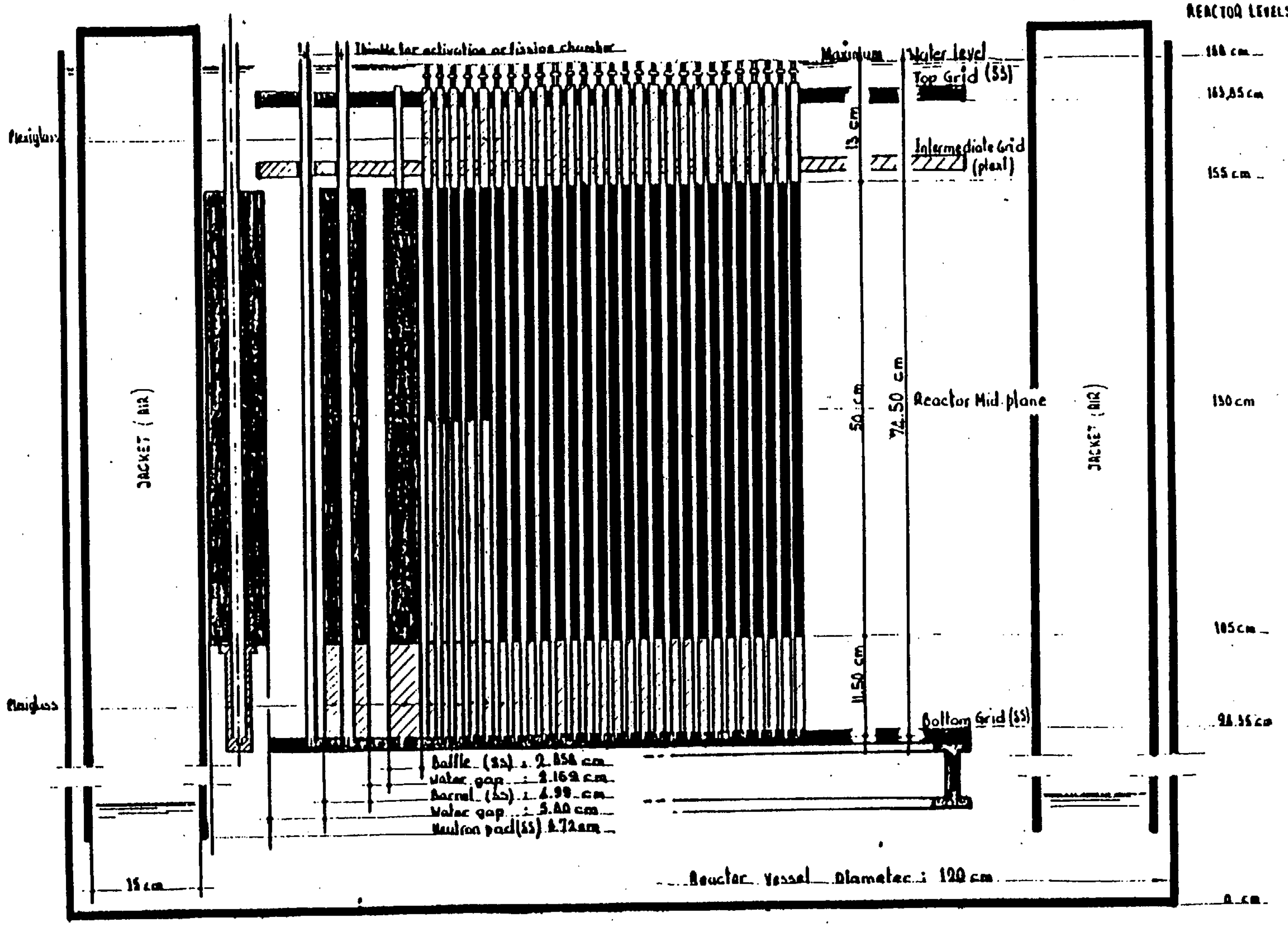
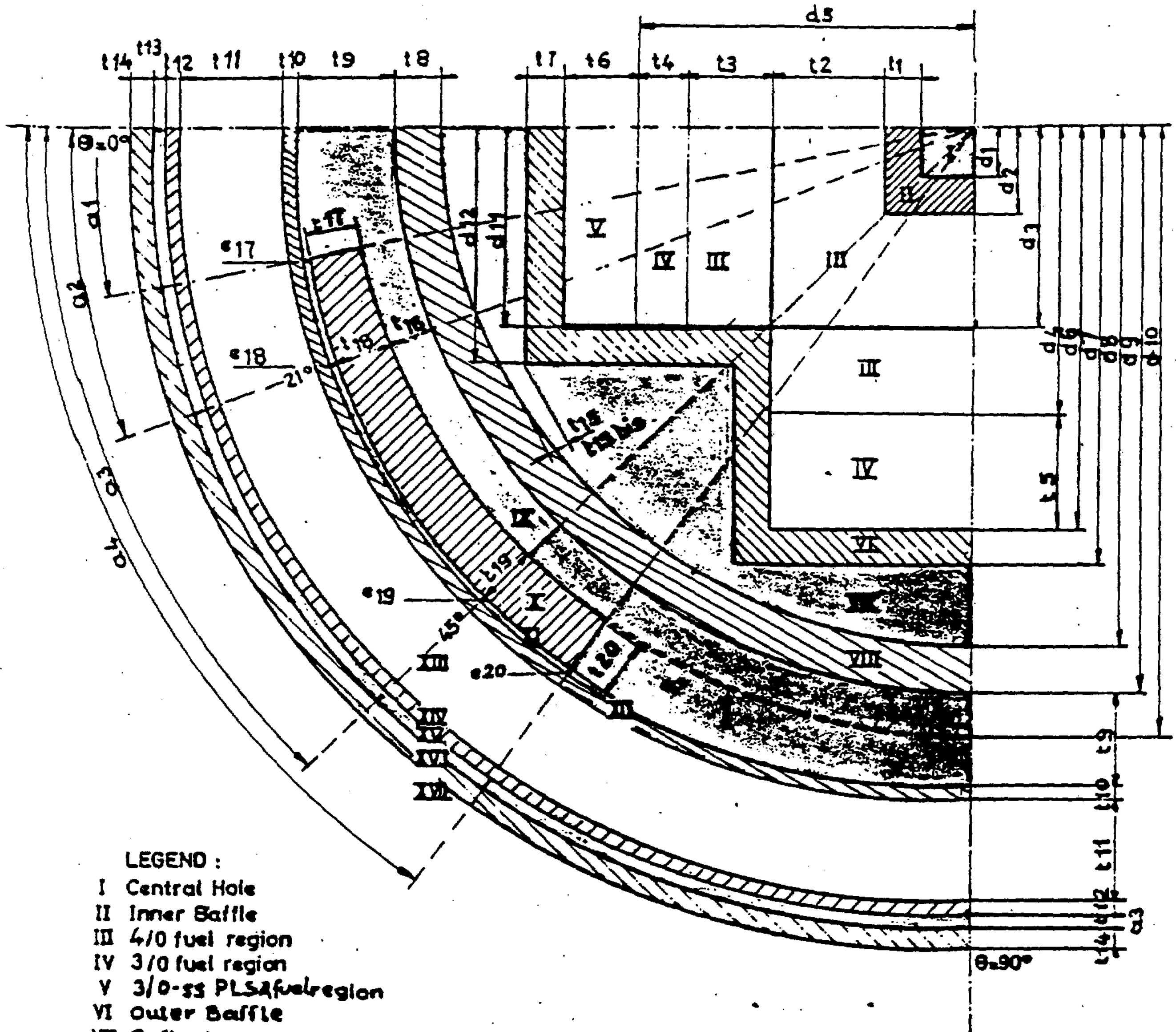



Fig. 1.4 : CORE DESCRIPTION (Vertical cross-section)

CEN / SCK - MOL

VENUS CRITICAL FACILITY

LWR - PVS - BENCHMARK : VENUS-3 (PLSA)




LEGEND :

- I Central Hole
- II Inner Baffle
- III 4/0 fuel region
- IV 3/0 fuel region
- V 3/0-SS PLSA fuel region
- VI Outer Baffle
- VII Reflector
- VIII Barrel
- IX Watergap
- X Neutron Pad
- XI Space between Pad and Jacket
- XII Jacket inner Wall
- XIII Jacket
- XIV Jacket Outer Wall
- XV Water
- XVI Reactor Vessel
- XVII Reactor Room

COLOURS:

- Fuel region or air
- Stainless Steel
- Water
- Water and Stainless Steel
- Aluminium
- Plexiglass

Fig. 1.5 : CORE MODEL (Horizontal Cross-Section).

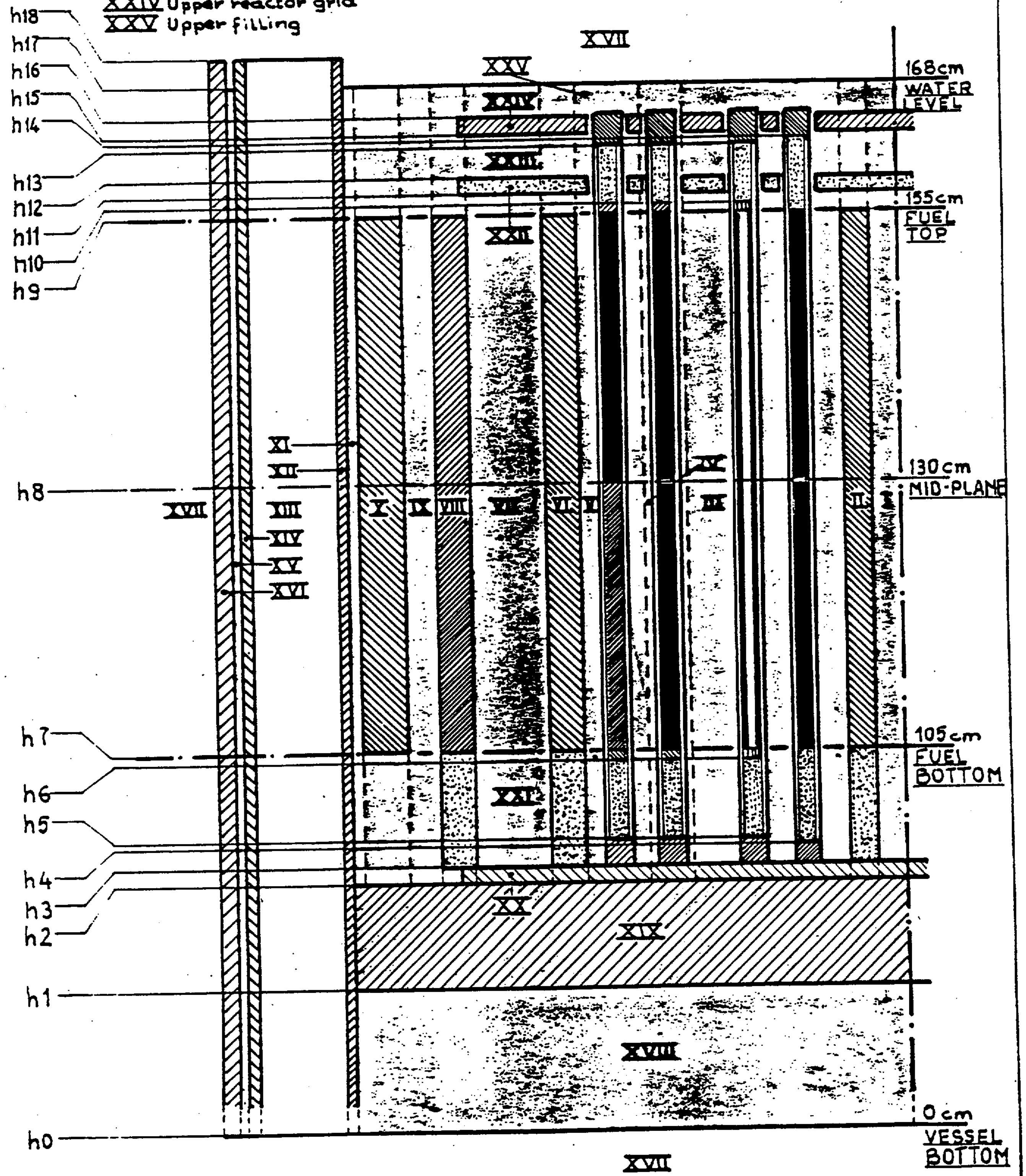
88/B3235/65089

:EN/SCK-MOL
/ENUS CRITICAL FACILITY
.WR-PVS-BENCHMARK : VENUS-3 (PLSA)

LEGEND: I to XVII, see Fig. 1.5
XVIII Lower filling
XIX Reactor support
XX Bottom grid
XXI Lower reflector
XXII Intermediate grid
XXIII Upper reflector
XXIV Upper reactor grid
XXV Upper filling

Fig. 1.6 : CORE MODEL
(Vertical cross-section)

Colours : see Fig. 1.5




88/B3235/65090