Institute for Nuclear Research – ICN Piteşti, ROMANIA
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INR- TRIGA Research Reactors a Neutron Source for Radioisotopes and Materials Investigation

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Introduction

- **At the INR there are 2 high-intensity neutron sources. These sources are in fact the two nuclear TRIGA reactors: 14MW TRIGA research reactor and TRIGA ACPR. (Annular Core Pulsed Reactor). Both reactors are open-pool type.**

- **TRIGA 14MW research reactor**

- **TRIGA reactor stationary core, Fig.1, operated by the Institute for Nuclear Research in Pitesti, Romania, has a rectangular shape which holds fuel bundles. Each fuel bundle is composed of 25 nuclear fuel rods containing LEU and the fuel bundle has 89 mm^2 cross section. The reactor core is surrounded with 20 beryllium reflector with 33mm central hole and 24 without hole. Beryllium reflector square cross section is identical with fuel bundle**

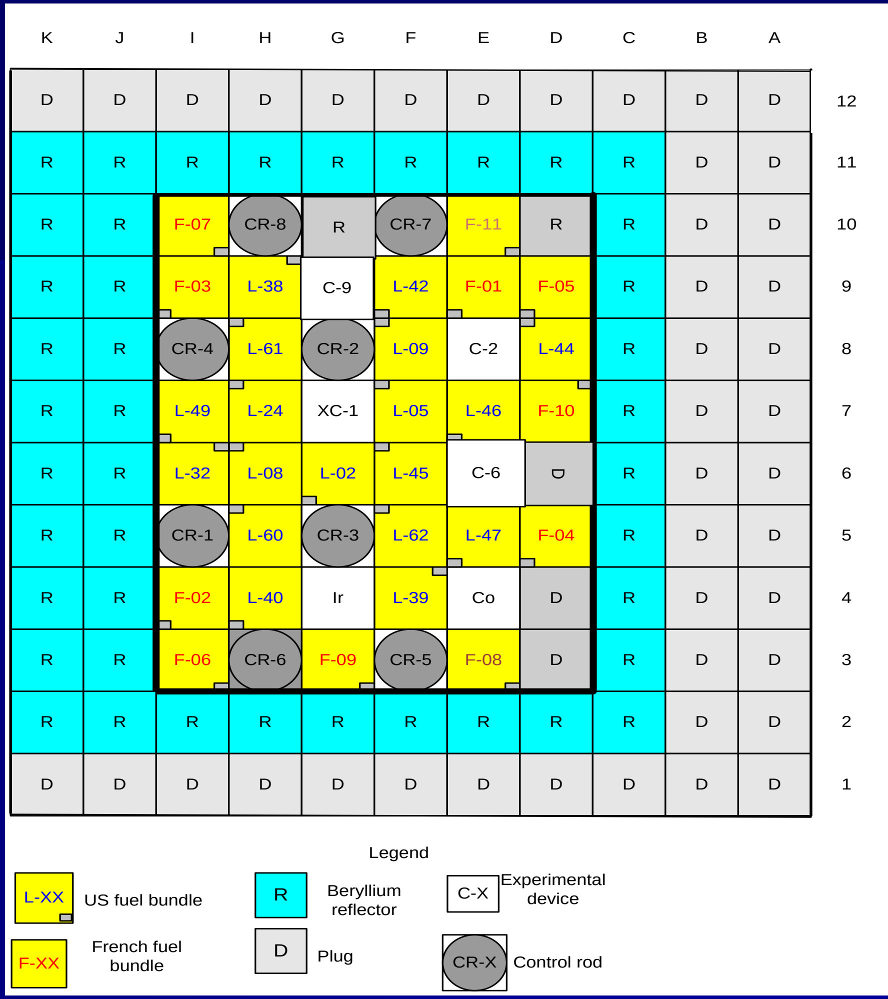


FIG. 1. Layout of TRIGA14MW reactor core

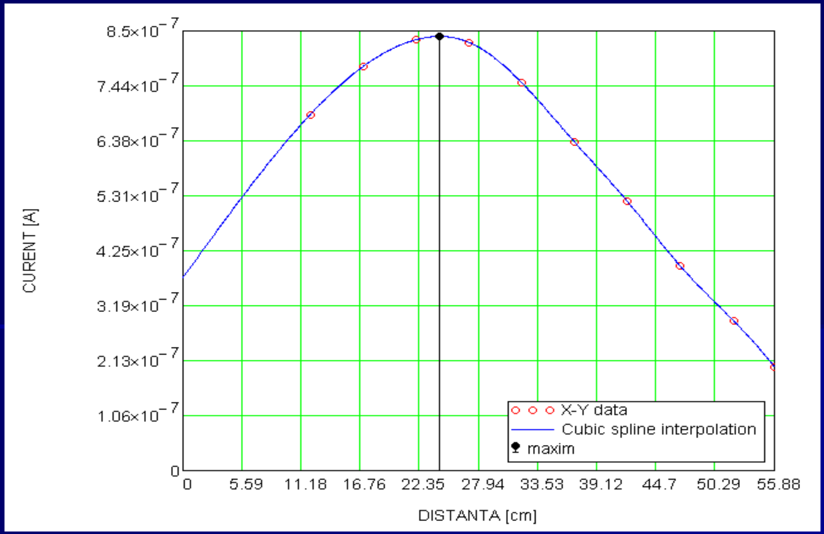


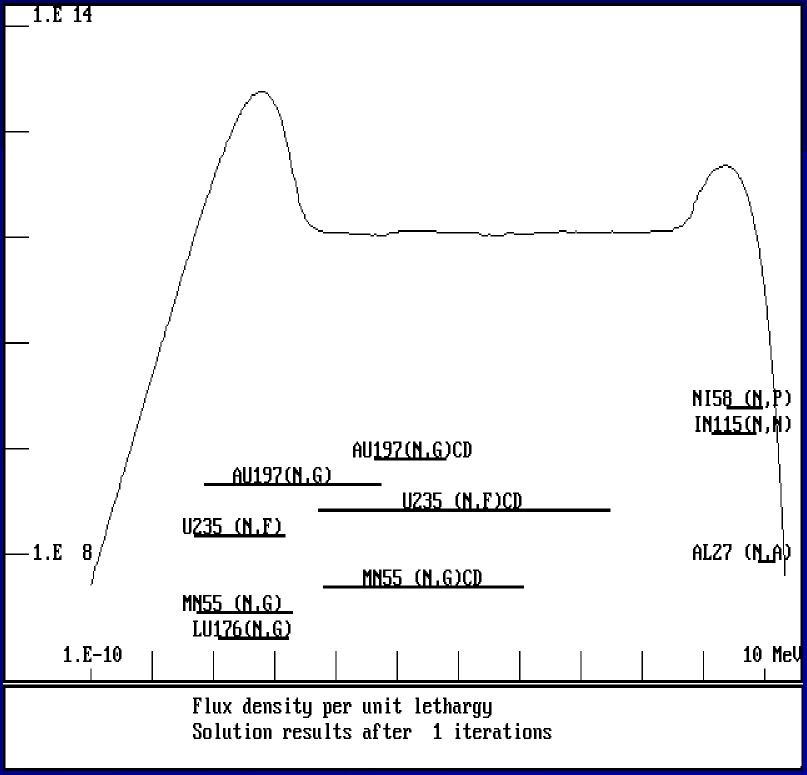
FIG.2. Thermal neutron flux axial distribution in XC-1 channel

The thermal neutron flux spectrum in XC-1 core channel was determined using the selected multi-foil activation technique. The flux density per unit lethargy spectrum output of SAND2 code on 621 energy groups for XC-1 water filled irradiation channel is shown in Fig. 3

The maximum value of the thermal neutron flux having the energy lower Cd cut-off energy (E_{Cd}=0.55eV) for 14MW reactor power is: Φ_{Scd} = $2.46*10^{14}$n/cm^2*s

Integrated neutron flux (0<E>18MeV) is: Φ = $3.86*10^{14}$n/cm^2*s

Cadmium ratio, R_{Cd}, respectively thermal to epithermal neutron flux ratio, f, are: R_{Cd} = 3.02, f = 31.56



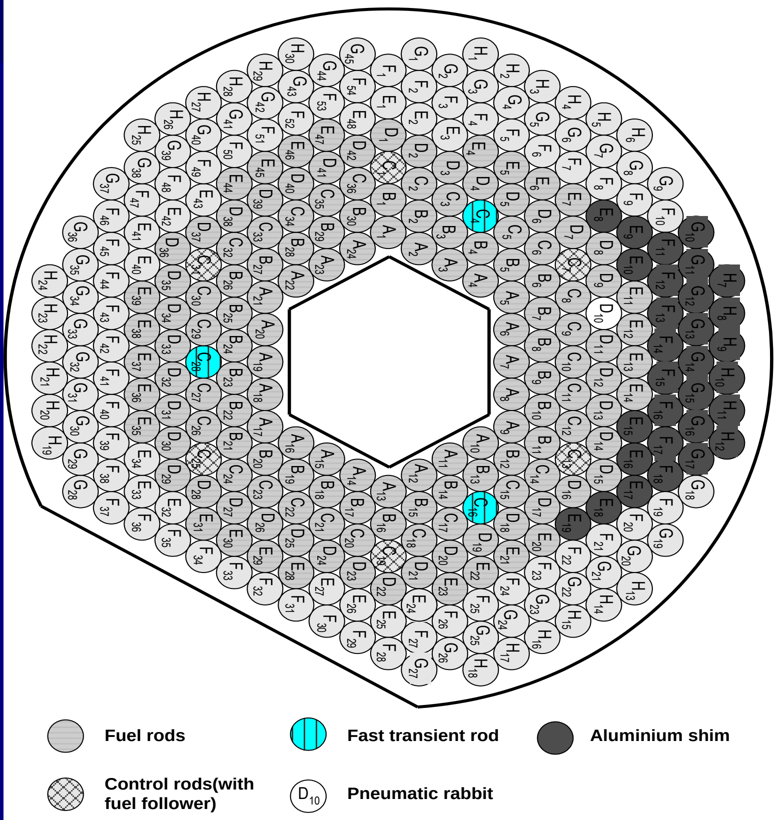
Neutron characteristics

Beryllium reflector block J-6

- $\Phi_{Scd} = 9.17*10^{13} n/cm^2*s$
- **K-11 beryllium reflector block :**
- $\Phi_{Scd} = 8.28*10^{12} n/cm^2*s$
- The 14MW TRIGA SSR reactor is also provided with a horizontal radial dry neutron beam tube having a diameter of 280mm. The thermal neutron flux at the beam tube inlet is: $\Phi_{Scd} = 1.7*10^{13} n/cm^2*s$

TRIGA ACP Reactor

- The secondary high-intensity neutron source from Institute for Nuclear Research, Pitesti, is TRIGA Annular Core Pulse Reactor



ACPR – Main Characteristics

Technical specification	Measurement units	
Steady State Power	Up to 500kW *Suitable for tests and calibration measurements for very low power levels*	
	Pulse Operation	
Maximum Pulse Power	20000 MW	
Minimum Period	1.2msec	
Pulse Width	4.6 msec 1/2 pulse	
Fuel	Type	12 wt% U-ZrH fuel
	Enrichment	20 % ^{235}U
	Cladding material	stainless steel with dimples
	Diameter	3.56 cm
	Rods number	146+6 fuel followers
Control Rods	Type	fuel flowered type
	Poison material	natural B_4C
	Number	*6*
	Rod drive	rack and pinion, electromagnetic connection with the control rod
Transients Rods	Number	2 fast transient rods and 1 adjustable transient rod
	Type	air followered
	Poison material	92% enriched B_4C
	Rod drive	fast: pneumatic adjustable: rack and pinion drive
Maximum Thermal Flux	$1.0x10^{17}$ n/cm^{2}s	
Maximum Fast Flux	$1.0x10^{16}$n/cm^{2}s	
Pool	10m depth, 5 m width, 9m length	

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- For stationary mode operation at P=100kW the thermal neutron flux in central dry irradiation channel is:

$$\Phi_{Scd} = 5.03*10^{12} n/cm^2*s$$

- Fast neutron flux (E>0.1MeV) and f factor is:

$$\Phi_f = 4.7*10^{12} n/cm^2*s; f = 4.67$$

- Thermal neutron flux in the pneumatic rabbit from dry channel D10 at P=100kW in stationary mode and f factor are:

$$\Phi_{Scd} = 4.68*10^{12} n/cm^2*s; f= 12$$

- This reactor is provided with two dry horizontal beam tubes having an inner diameter of 280mm, total length of 5m, one of them being radial and other tangential.

Activities developed at INR TRIGA Reactor

- Neutron Activation Analysis Techniques
- Neutron Scattering
- Neutron Radiography
- Radioisotope Production
- Material Investigation

Neutron Activation Analysis Techniques
In core irradiation devices for NAA

Two pneumatic rabbit: For the beryllium channels, a pneumatic rabbit with cartridge dimensions of: 12 x30mm is available. This pneumatic rabbit is manually operated. Another irradiation device, also of pneumatic rabbit type, is provided with an underwater storage rack having a capacity of 12 cartridges. It has an automatic timing control.

Gamma spectrometers and software analysis package

- three high-resolution gamma ray spectrometers are available
- All gamma ray detectors are HpGe type having relative efficiency of ~20%.
- Two of the spectrometry chains are provided with an AQUSPEC multi-channel analyzer and GENIE2000 software analysis package

NAA METHOD

- Zr standardization method
- The method is based on the two specific neutron capture reaction of zirconium: ^{94}Zr(n,)^{95}Zr and ^{96}Zr(n,)^{97}Nb. These reactions allow us to calculate the thermal to epithermal neutron flux ratio, and also of the elemental concentration in the analyzed samples.
- K_0 standardization method

Cont'd

- Usually, for NAA purposes beryllium reflectors channels are used but also in-core irradiation channels can be used for above mentioned purposes. The neutron flux parameters in K-11 beryllium channel are :

TABLE 1. Neutron spectrum parameters of the K-11 irradiation channel

Parameters	Mean	±	SD (k=1)
α	0.0116	±	0.0020
R_{Cd}	3.75	±	0.94
f	48.63	±	1.82
Φ_{th}	$8.30*10^{12}$	±	$1.67*10^{11}$

TABLE II. Certified and experimental elemental concentration in ECRM 379-1

	Reference values			Measured average values		
No#	Element	Concentration (%)	Stdev (k=3)	Concentration (%)	Stdev (k=1)	Diff (%)
1	Mn	1.84	0.17	1.83	0.25	0.53
2	Ni	30.83	0.06	30.23	1.20	1.95
3	Cu	0.983	0.08	0.95	0.08	3.81
4	Cr	26.77	0.04	26.71	0.16	0.22
5	W	0.01	0.0001	0.0104	3.8E-04	-4.2
6	Mo	3.29	0.11	3.33	0.15	-1.07
7	Fe	35.7	0.04	35.97	1.30	-0.77
8	Co	0.0384	0.001	0.038	0.002	2.21
9	As	0.0028	0.0001	0.0029	1.75-04	-1.79
10	Sb	5.70E-04	0.0001	5.60E-04	3.40E-05	1.75
11	V	0.066	0.002	0.064	3.84E-03	3.03

Prompt Gamma Neutron Activation Analysis

At INR Pitesti, a prompt gamma ray NAA (PGNAA) has been designed, manufactured and put into operation. It is linked to the horizontal radial beam tube of the TRIGA pulsed reactor. For PGNAA purposes, the pulsed reactor is operated in stationary mode. A schematic layout of this facility is shown in Figure 5

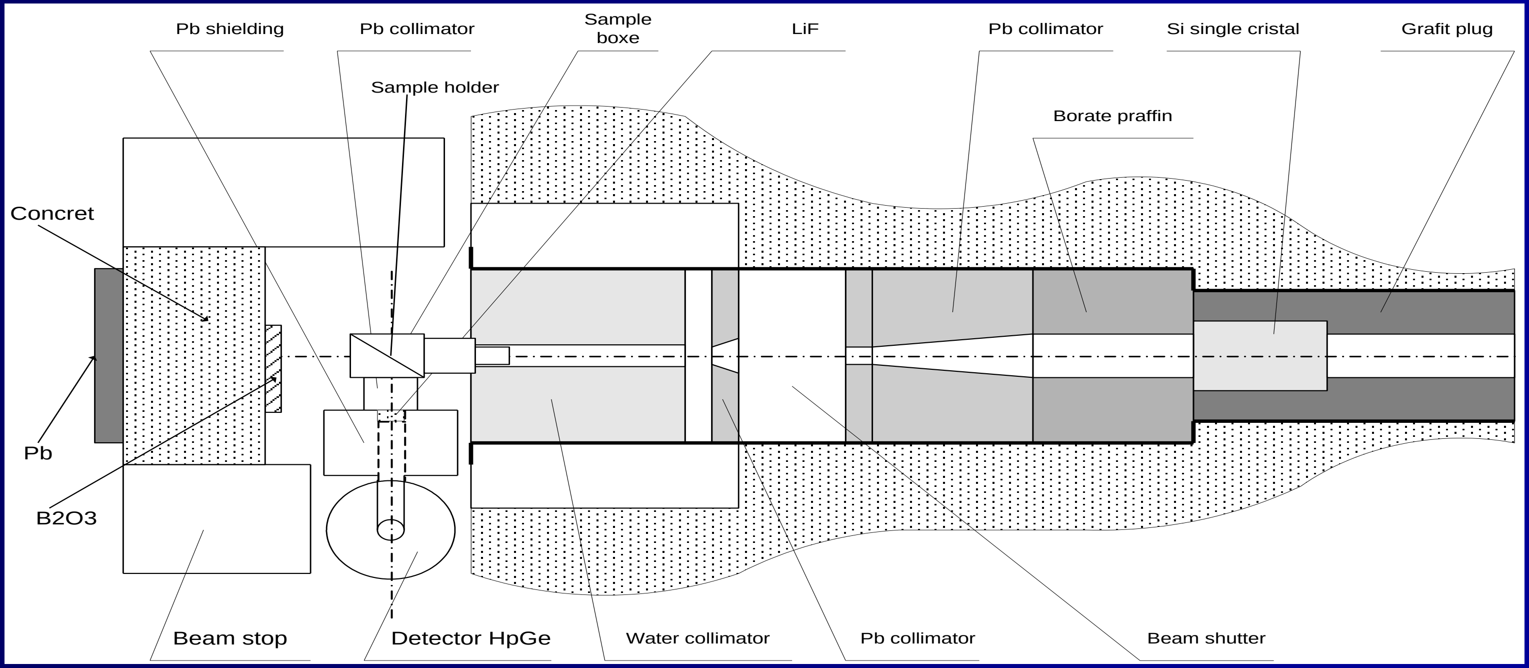


FIG. 5. PGNAA schematic layout

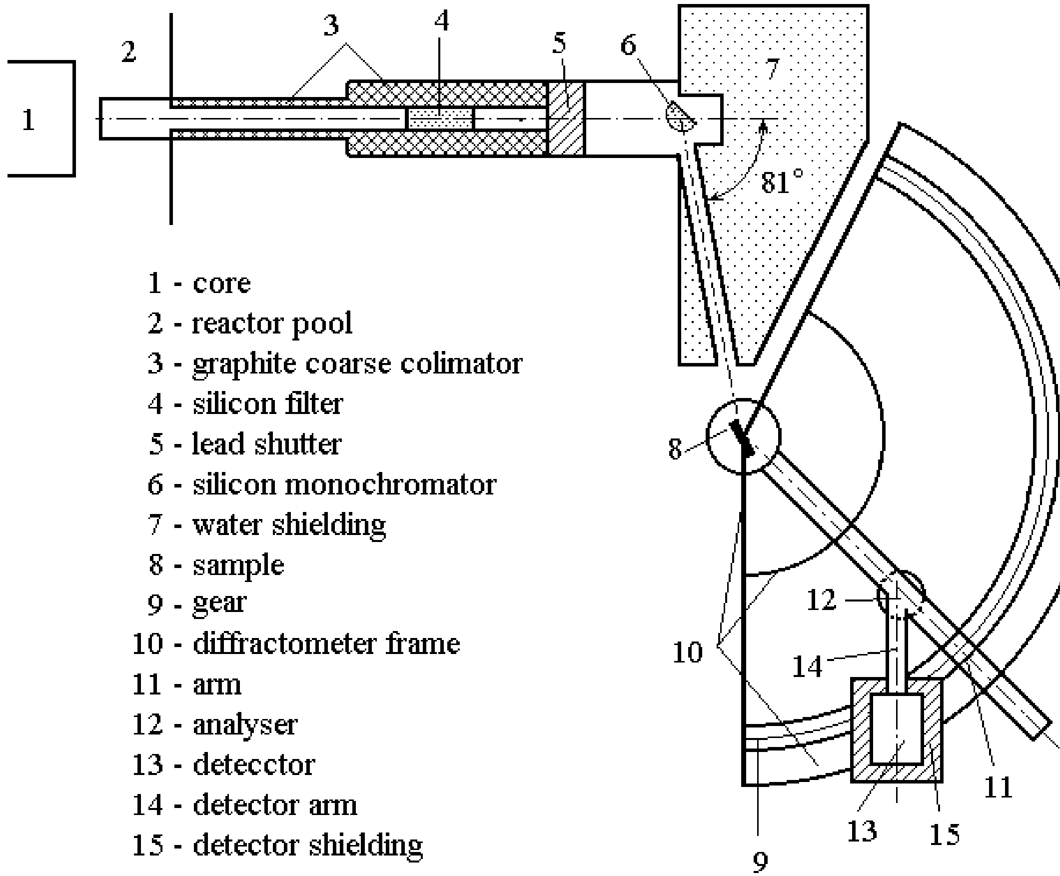
- The thermal neutron flux ($E<E_{Cd}$) measured by gold foil activation method and the cadmium ratio are: $\Phi_{scd} = 1*10^6 n/cm^2*s$; $R_{Cd} > 40$.

The beam shape at the sample holder obtained by radiographic method is shown in Figure. 6. In the radiographic film a circular spot was observed, 50mm in diameter, having a good contrast and slightly diffuse edge and being very homogenous.

High resolution neutron diffractometer

- A focusing high-resolution neutron crystal diffractometer has put in operation at the Institute for Nuclear Research Pitesti, Romania. A new concept of high-resolution neutron diffractometer has been developed in the Institute for Nuclear Research Pitesti. This kind of configuration allows high resolution performances to be achieved, comparable with the best existing conventional diffractometers, even for medium flux neutron sources ($10^{13} – 10^{14}$ n/cm^{2}sec) and therefore gives special opportunities for the most of the existing research where medium flux neutron sources are available.
- High-resolution neutron diffractometer is used for structural examinations of polycrystalline samples (including superconductors), stress determinations or hydrogen concentration evaluations by measuring diffraction line integral intensity.

High resolution neutron diffractometer

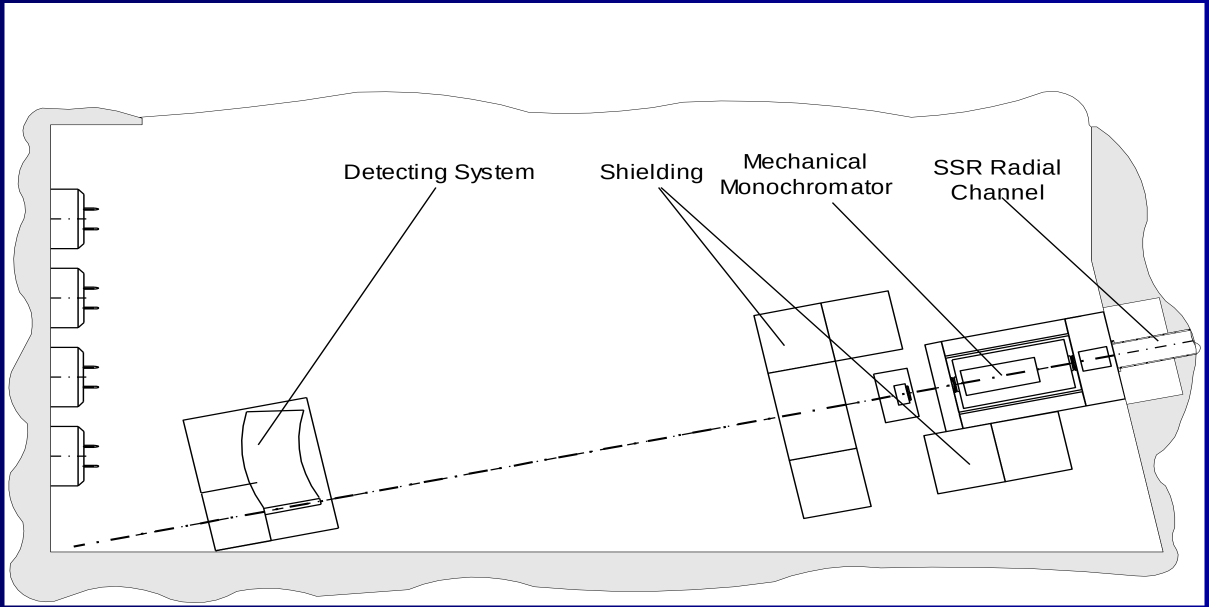


High resolution neutron diffractometer

- monochromatic beam take-off angle 83^0
- wave-length 1.3855 Å
- silicon perfect crystal monochromator (100) plane (200 mm diameter, 3 mm thickness)
- the reflection plane (511)
- "the cutting angle" $\chi_m = -15.8^0$
- source-monochromator distance = 5200 mm
- monochromator-sample distance = 2800 mm
- sample-detector distance = 1200 – 3000 mm
- detector window range 0-10mm
- sample positioning using a step-by-step motor

Small Angle Neutron Scattering

At INR Pitesti the performance of SANS facility is under characterization. The application of SANS at lower power reactors and in developing countries nevertheless is possible in well selected topics where only a restricted Q range is required, when scattering power is expected to be sufficiently high or when the sample size can be increased at the expense of resolution.



Neutron Radiography Facility

- The underwater neutron radiography facility placed near the TRIGA pulsed reactor core (ACPR) was used with good results for the examination of the irradiated and unirradiated nuclear fuel pins. Were investigated TRIGA-SSR (HEU and LEU) pins, experimental CANDU pins and also a damaged control rod.
- There are used two methods:
- - The transfer method. A dysprosium or indium screen is the converter of the neutron incident radiation into secondary ionizing radiation. The recorder of the image is an industrial radiographic film, AZO type in three speed ranges: NG1, NG2 and NG3. The image obtained has 385 mm by 98 mm.
- The track-etch method. It is used a cellulose nitrate film, the type CA 80 15B with the dimensions 90 mm by 300 mm. A solution of 10% of NaOH at 50 Celsius degree temperature is used for an hour cellulose nitrate film etching.

Underwater neutron radiography facility

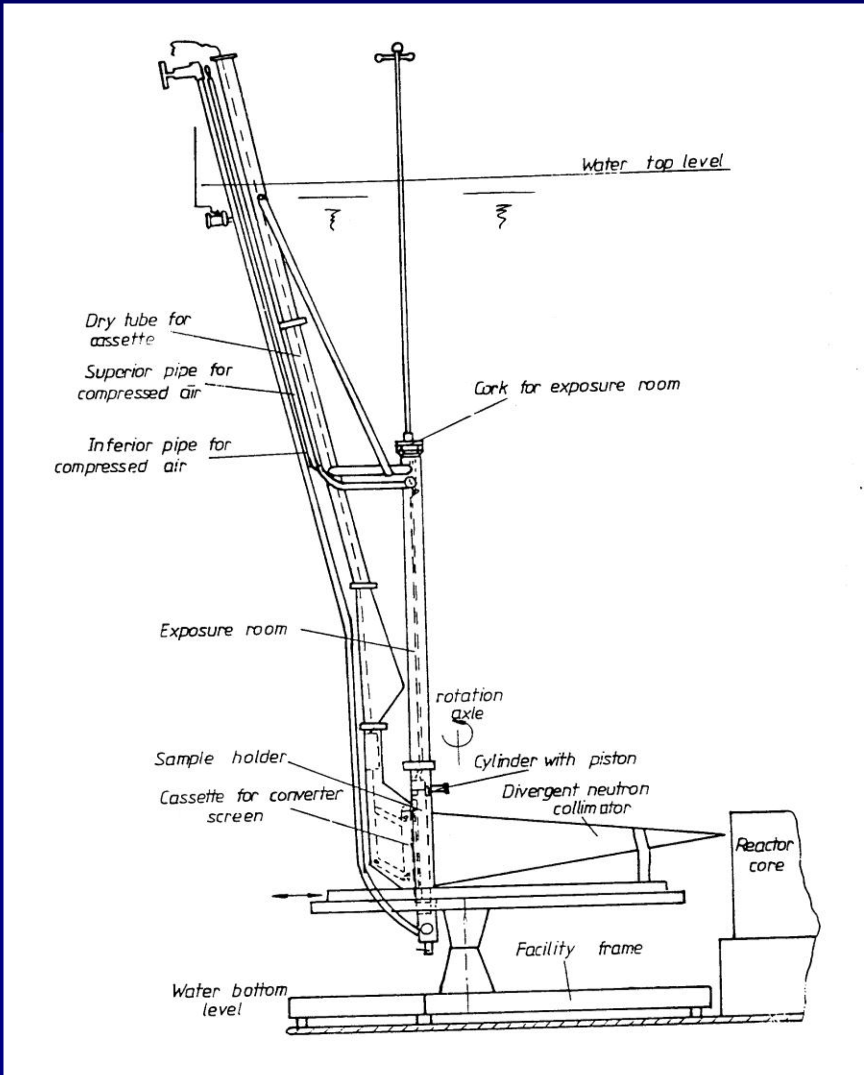
The divergent neutron collimator L/D ratio = 250

The window exit of the collimator (and the image dimensions) = 385 mm x 100 mm

The neutron beam intensity = 5 x 10^6 n/cm^2/s (in the plane of the object)

The geometric unsharpness =60 μm

The image is with 0.735 % bigger than the object.



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Experimental CANDU nuclear fuel pins

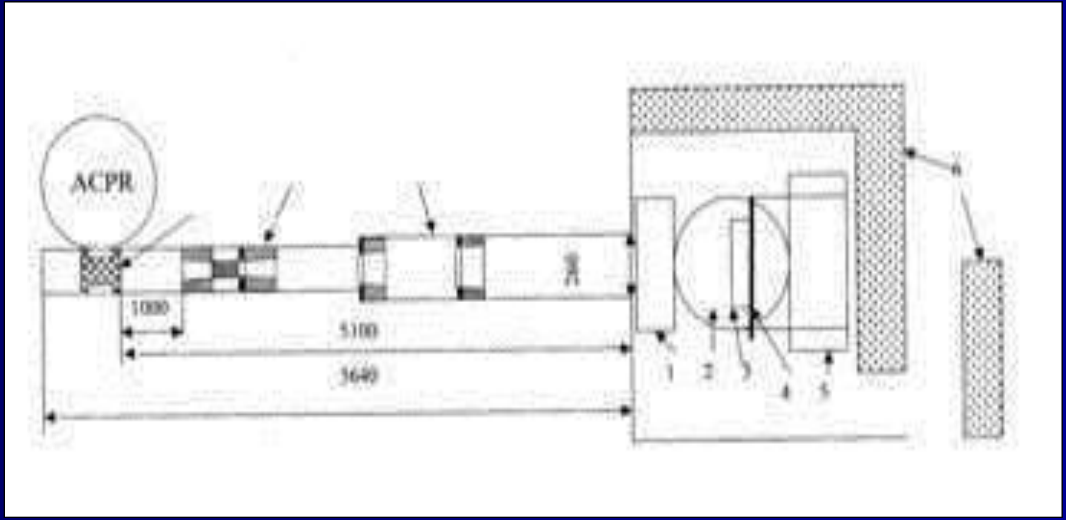
TRIGA-HEU, TRIGA-LEU (fresh and irradiated fuel pins) and a dimensional standard

TRIGA-LEU fresh fuel pin and image quality indicators

Dry neutron radiography facility

The new dry neutron radiography is linked to the horizontal tangential beam tube of TRIGA ACPR reactor;

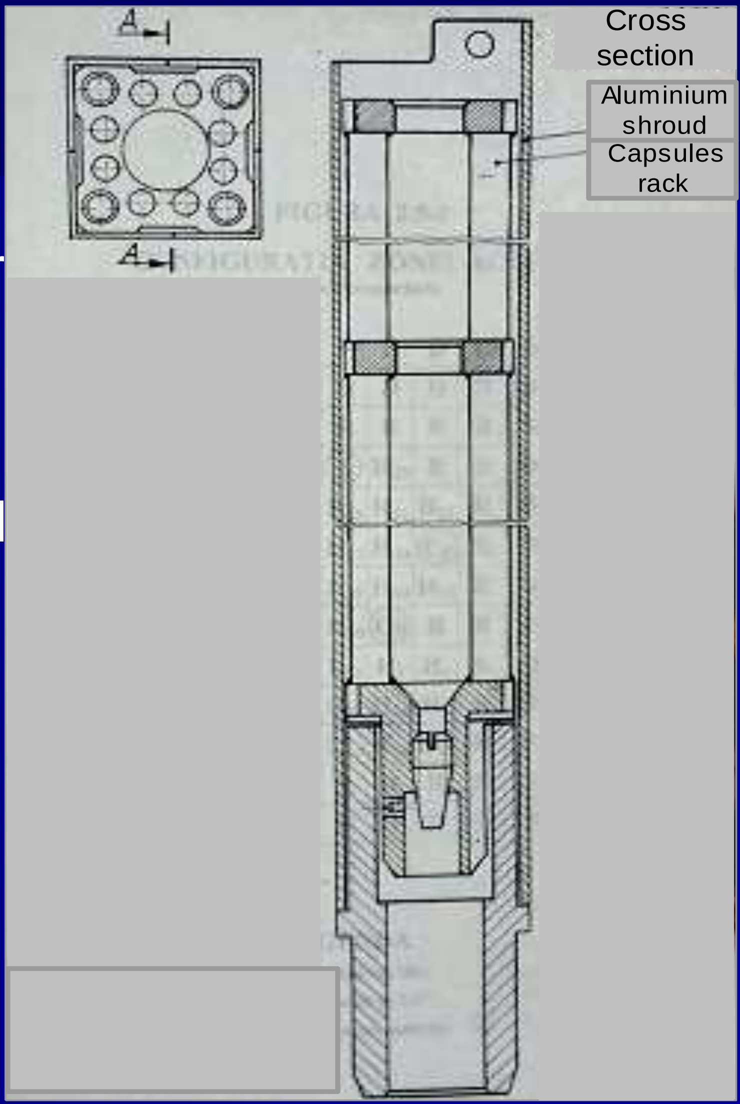
The collimation of the neutrons on the tangential beam port of the ACPR reactor is done, in fact, with a pin-hole collimator with an aperture of 45 mm placed at the distance of 125-152.5 cm from the surface of the illuminator that has a thickness of 7 cm and the diameter of 18 cm. The estimated beam intensity for thermal neutrons with bismuth filter is $3.96 \cdot 10^5 - 4.65 \cdot 10^5 n/cm^2$ and $4.85 \cdot 10^5 - 5.70 \cdot 10^5 n/cm^2$ without Bi filter.



Radioisotope production

TRIGA 14MW reactor has been designed also for radioisotope production (for medical and industrial use). The design of reactor core allows using in the same time different irradiation channel for isotope production. For short half-life radioisotope production the Beryllium reflector vertical irradiation channels are used, for which load / unload operations can be done during reactor normal operation.

- A versatile irradiation system uses the standard TRIGA fuel shroud with grids, which can accommodate up to 9 thin-walled re-usable Zircaloy irradiation pins . Each pin can receive up to 40 Iridium disks in reusable capsules, or various other capsules. Iridium targets are obtained in INR's laboratories.



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Co Capsules

Ir Capsule

Pin holders with capsules

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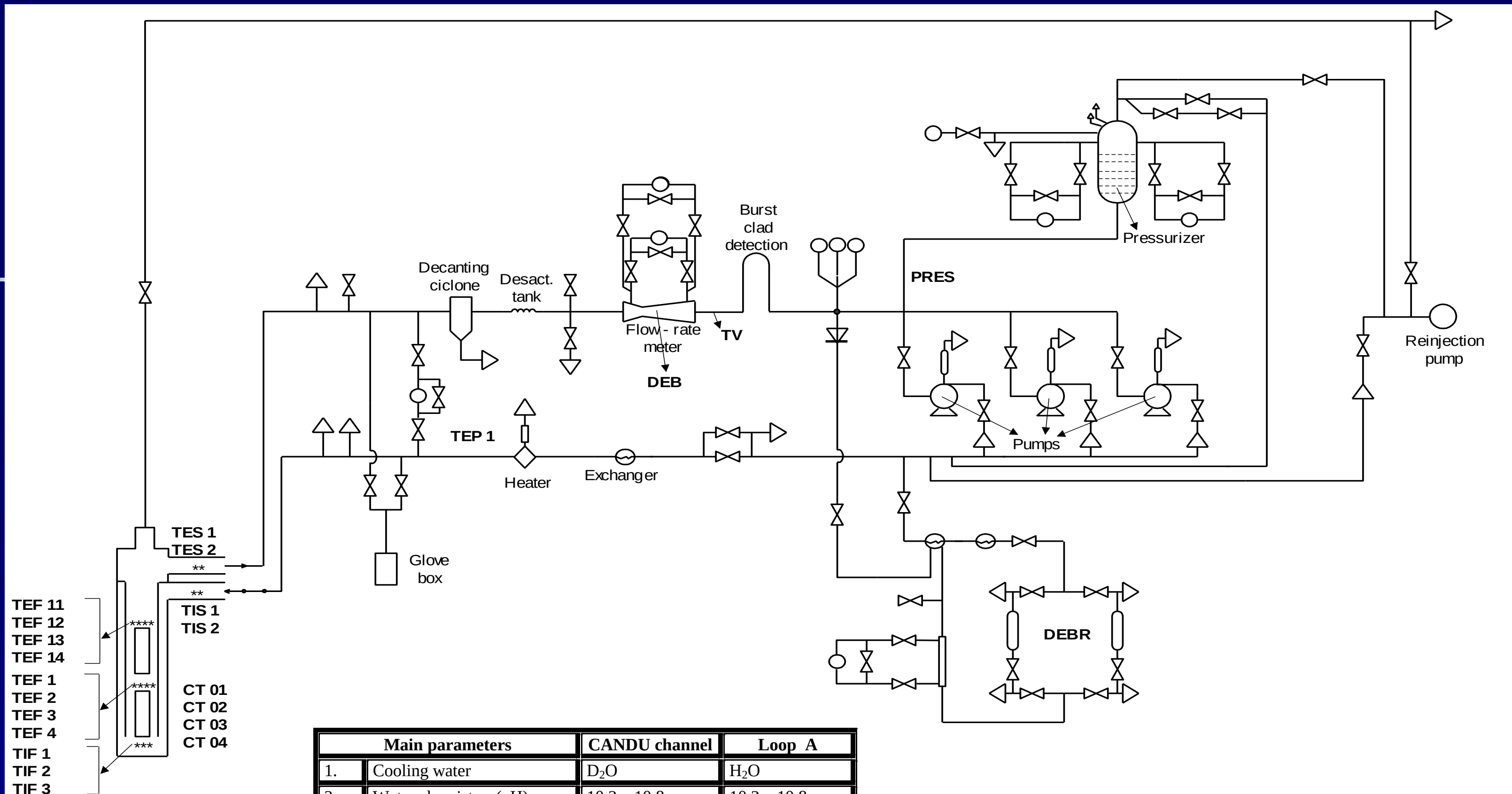
- INR has got licenses for ^{192}Ir, ^{60}Co bulk or sealed sources and ^{131}I and ^{125}I production.
- Now, INR is involved in implementation of CINTECHEM technology for ^{99}Mo-^{99m}Tc radioisotope production by irradiating Nickel-coated LEU targets. A new irradiation device has been designed, manufactured and tested. For ^{99}Mo production the high flux XC-1 irradiation channel will be used.
- The isotope production is advantaged by the quick access to the neighbouring hot cells

MATERIAL INVESTIGATION

- For nuclear fuel behavior under special irradiation conditions several irradiations devices are available (capsule, loop etc).
- The LOOP A irradiation device is designed for CANDU nuclear fuel testing in the same conditions as in CANDU pressure tube except the cooling agent (pressure, temperature)

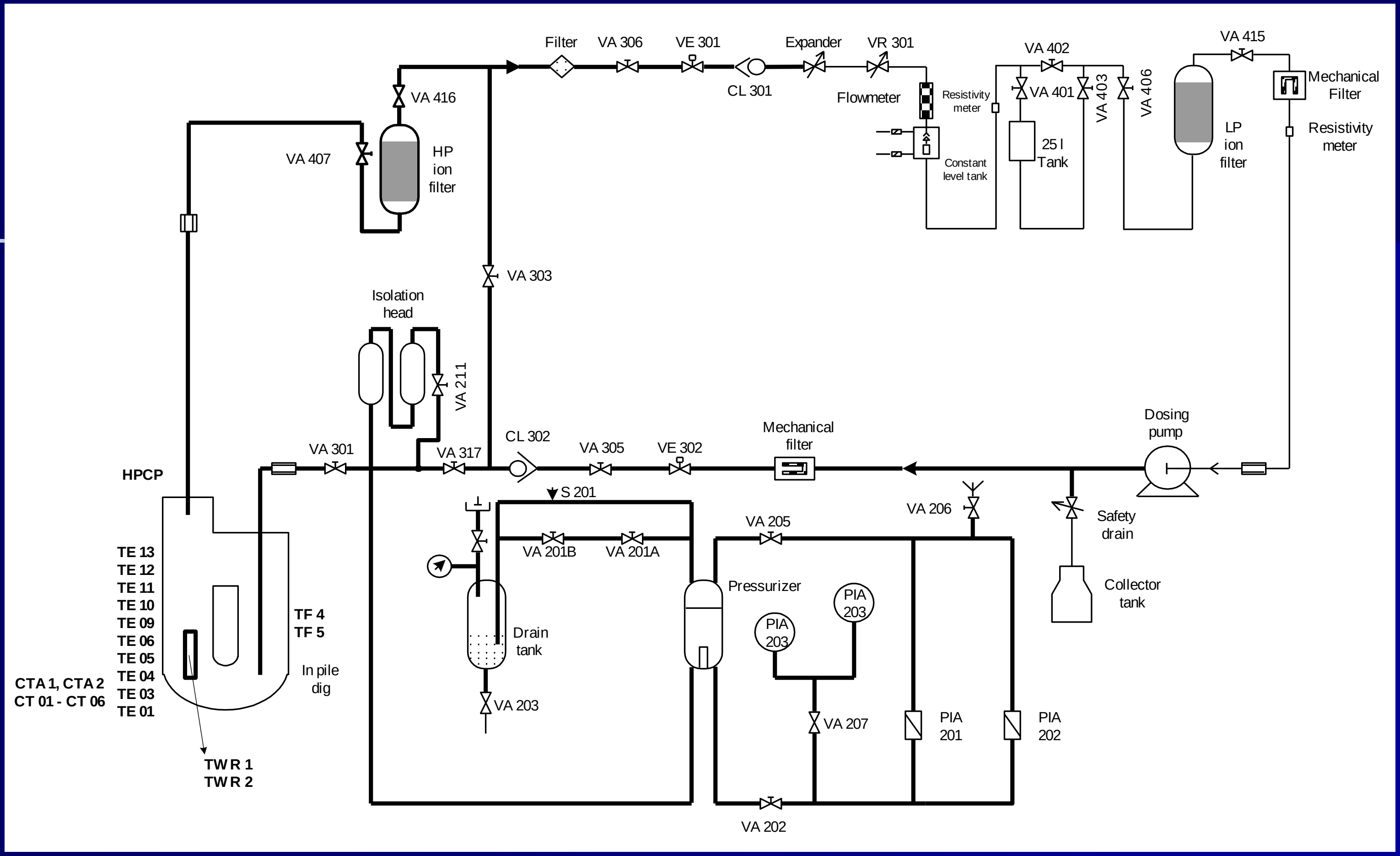


	Main parameters	CANDU channel	Loop A
1.	Cooling water	D_2O	H_2O
2.	Water chemistry (pH)	10,2 – 10,8	10,2 – 10,8
3.	Temperature		
	- input in channel	266°C	<297°C
	- outup from channel	312°C	310 °C
4.	Pressure		
	- input in channel	111 bars	<120 bars
	- outup from channel	102 bars	114 bars
5.	Water flow rate	10,4-26,7 kg/s	1,5 kg/s
6.	Specific power / fuel pin	450 W/cm	550 W/cm max.

Loop A flow Sheet

	Irradiation Test	Irradiated Nuclear Fuel
1.	Overpower test	EC10, EC11, EC12
2.	Overpower test	EC35, EC36, EC37
3.	Power ramp test	EC15, EC16, EC18, EC19, EC76, EC77
4.	Power ramp multiple test	EC80, E C81, EC82, EC84, EC85, EC86
5.	Power ramp multiple test	ECA01, ECA02, ECA03, ECA04, ECA05, ECA06
6.	High burn - up power ramp multiple test	ECA28, ECA30, ECA34, TR1, TR2, TR3
7.	Cernavoda NPP Zr - 2.5%Nb pressure tube samples irradiation	• Corrosion – 48 samples: 24 in flux, 24 out of flux • Mechanical properties 24 samples: 12 in flux, 12 out of flux

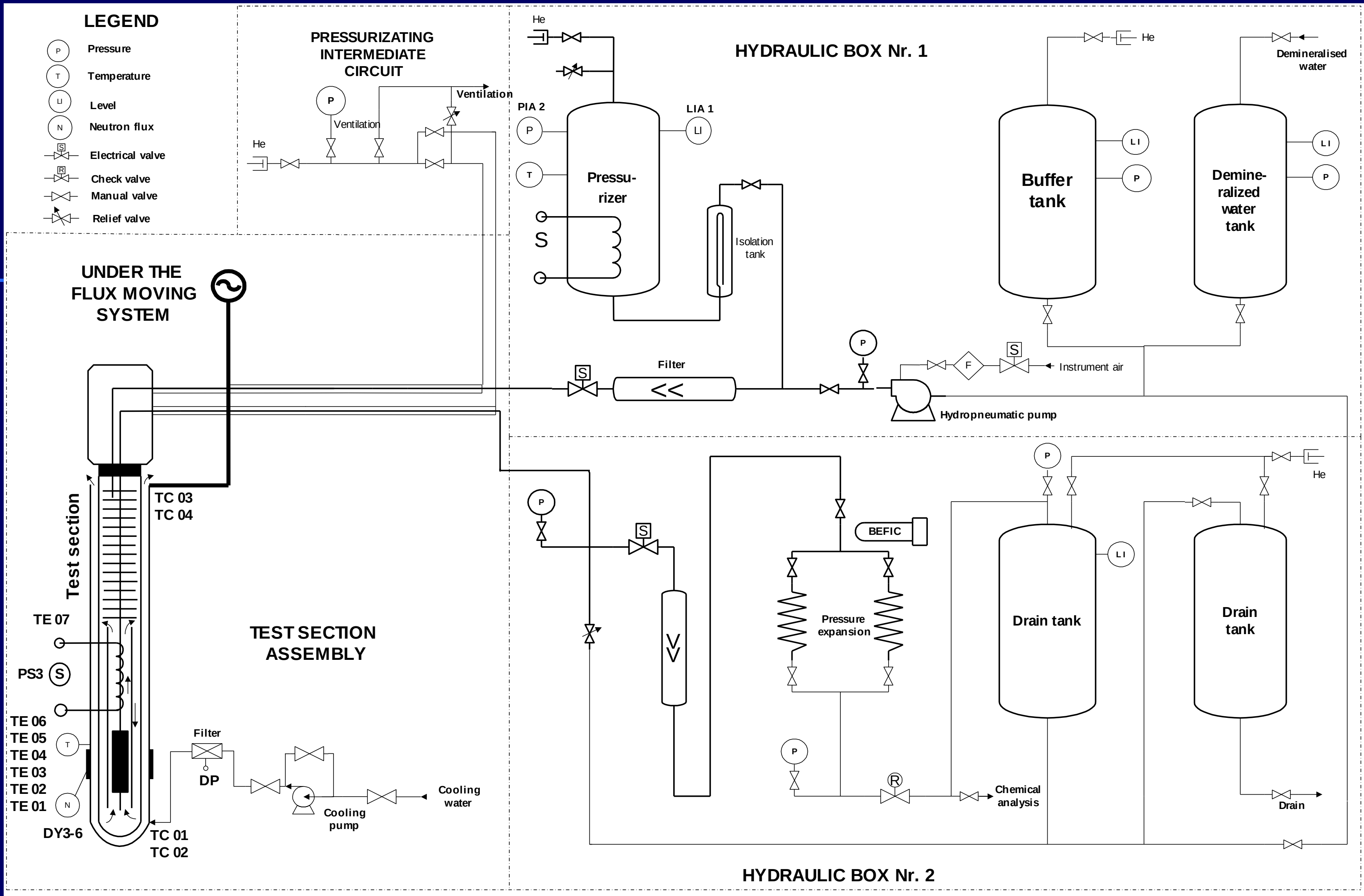
The tests developed in Loop A



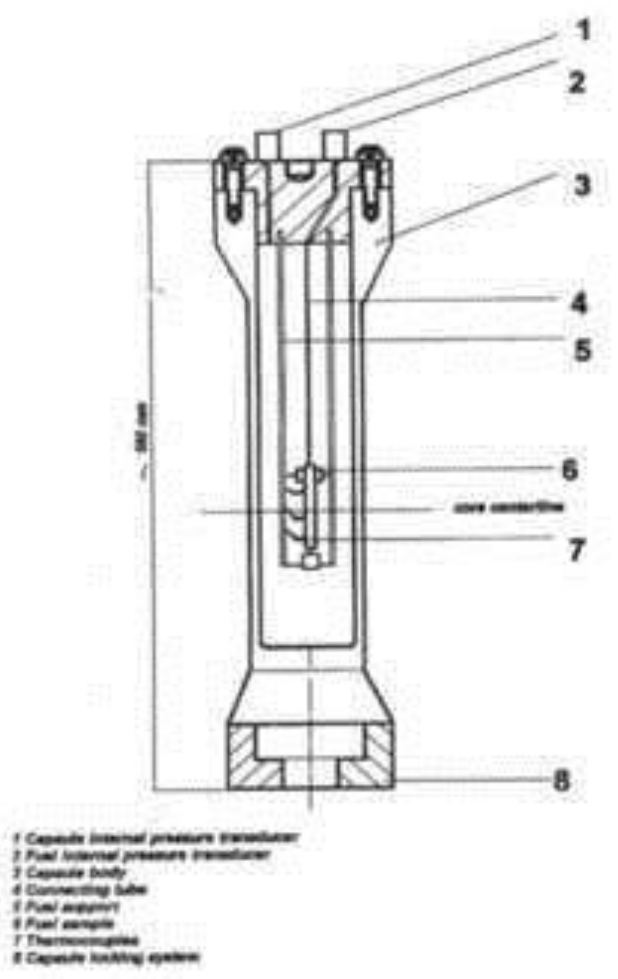
Capsule C2 Flow Sheet

Experiment	Irradiation period	Fuel element	Sample holder
Dimensional measurement	Oct ÷ Dec.1981 May ÷ Jun.1983	EC1	MD1 ACB France
Fission gas pressure	26.03÷31.03.84 19.04÷10.05.84	EC 24	PPF ACB France
Dimensional measurement	19.07÷31.08.84 17.09÷14.10.84	EC49	MD2 ACB France
Power ramp	03.12÷19.04.85 01.08÷11.11.85	EC 55	PS2-ACB PS1-ACB
Fission gas pressure	03.02÷16.05.86 07.07÷19.08.86	EC89	Romanian
Power ramp	03.12.86÷30.05.87	EC57	PS1-ACB France
Fission gas pressure	13.10÷26.11.87 16.12.87÷22.04.88	EC51	Romanian
Power ramp	09.05÷28.11.88 16.02÷29.05.89	EC 67 (EC 78)	PS1-ACB France
Power ramp	03.02÷16.05.86 07.07÷19.08.86 03.12.86÷30.05.87	EC Th-01	Romanian PS1-ACB France
Irradiation conditions calibrations	26.02÷01.04.92 23.04÷18.05.92 22.05÷26.06.92	EC A50	Romanian
Fission gas pressure	23.07÷16.12.92 25.02÷20.12.93 18.04÷21.09.94	EC A59 EC A60	Romanian
Residual deformation of the cladding d etermination	12.12÷13.12.96	EC B7	PS1
Central temperature measurement in the fuel	13.05÷13.07.98 11.09÷08.10.98	EC B2, B3	Romanian
Fission gases release effects on the temperature	15.05÷07.07.00 30.10÷07.11.00	EC B2, B3	Romanian
Res idual deformation of the cladding determination	05.12.2001	EC B8	PS1

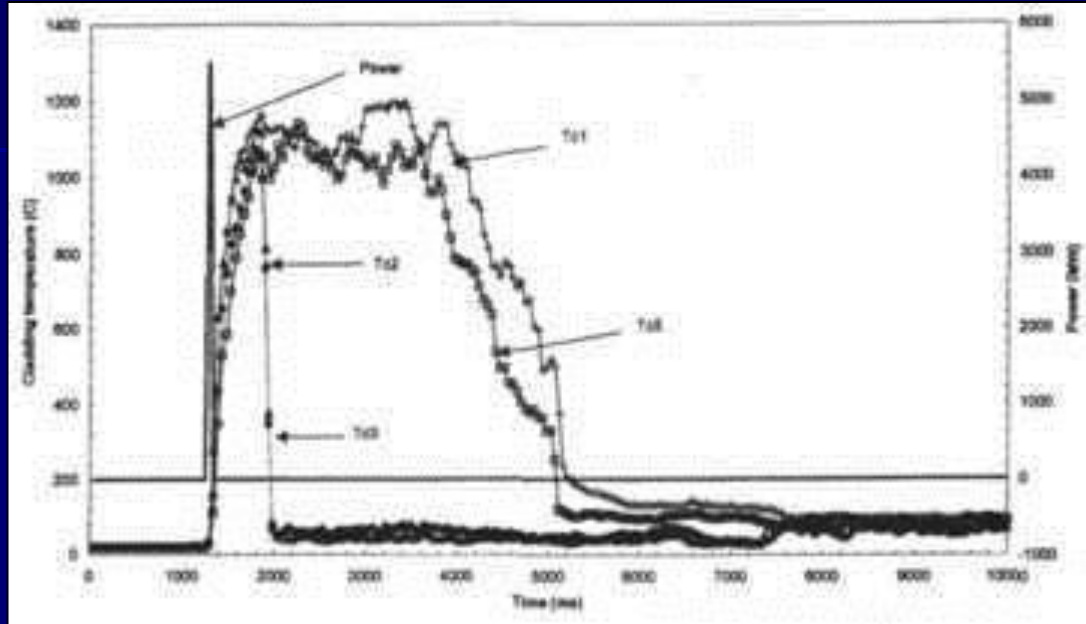
The tests developed in C2



Capsule C9 Flow Sheet



C6 Mechanical structure



Cladding surface temperature vs. reactor power

Post Irradiation Examination

- A hot cell for post test investigation (microscopy, composition, impurities, mechanical properties etc) is available.
- The **P**ost **I**rradiation **E**xamination **L**aboratory (PIEL) is builds a side of TRIGA reactor and is connected via an underwater transfer channel with reactor pool allowing the transfer of irradiation devices (lower part tubes) containing experiments in Hot Cells without casks and without disturbing irradiated materials. This facility allows intermediate/interim examination of samples and the continuation of irradiation of samples or to perform relocation of samples or replacement with some new one.
- The examination cell has 7 working station and allows visual inspection, mechanized measurement, gamma scanning or activity measurement of samples also cutting and machining of samples are available in inert atmosphere(i.e. dry nitrogen).

DESTRUCTIVE POST-IRRADIATION EXAMINATION TECHNIQUES

The nuclear fuel destructive PIE applied in the LEPI hot cells includes the following techniques

- Fuel rod puncture test;
- Optical microscopy;
- Chemical analysis and burn-up determination;
- Mechanical testing;

Conclusions

- The 14MW TRIGA Reactor in INR Pitesti is integrated in an assembly of facilities i.e. irradiation facilities, Hot Cells Post Irradiation Examination Lab., Radioactive waste conditioning plant and correlated with activities of a number of research programs developed by other departments of the Institute for our own needs and for international cooperation, is the key purpose built facility in operation and will support the nuclear research in Romania;
- **The results obtained by non-destructive and destructive examinationsof the fuel have enabled the CANDU fuel behaviour characterization after its testing in the TRIGA reactor both in normal operation and in accident conditions.**
- Good records of extensive utilization in the past, continuous efforts for upgrading the reactor core, made this young facility available for research and technological development for the next two decade..

Thank you for your attention!