RESULTS OF 14MW RESEARCH REACTOR CORE CONVERSION MEASURED AT LOW POWER

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Introduction

Characteristic for the last decades:

lack of new human resources

depreciation of a number of operating research reactors

decreasing the research infrastructure for nuclear power development

Introduction

14MW TRIGA research reactor, operated by the Institute for Nuclear Research in Pitesti, Romania

- relatively new reactor, commissioned 26 years ago;
- expected to operate for another 15-20 years
  - new fuel and testing of materials;
  - radioisotopes production;
  - sustaining research or enhanced safety;
  - extended burnup and verification of new developments concerning nuclear power plants life extension;
  - sustain neutron application in physics research;
  - becoming a center for instruction and training in the near future

Introduction

The pillars for the future utilization of the TRIGA Research Reactors and of the Post-Irradiation Examination Laboratory in Pitesti, Romania, are:

- **SAFETY, RELIABILITY AND AVAILABILITY;**
  - *a proved safety of the 14MW TRIGA-MTR*
  - *high flexibility of experimental and testing programs application correlated with post-irradiation laboratory*
  - *project of power increase to 28-30 MW in order to achieve a flux of 3-3.5x10^{14}n/cm^2s*
  - *full core conversion (done in 2006)*
  - *existence of an European reliable fuel manufacturer*
  - *complementary utilization of Annular Core Pulse Reactor ((TRIGA-ACPR) for special safety experiments*
  - *no major issues concerning the spent HEU fuel return in the country of origin and solutions until the horizon of 2019 for LEU fuel*
  - *a large refurbishing and modernization program undertaken to cope with ageing and obsolesce of equipment and to satisfy the actual requirements in terms of safety and reliability which will be accomplished during the next year*
- **INTERNATIONAL COOPERATION AND UTILIZATION FOR RESEARCH ON THE DEVELOPMENT OF NEW MATERIALS FOR POWER REACTORS**
- **INCREASING ENERGY DEMAND**

Introduction

The gradual full conversion of the core was a necessary step to ensure the continuous operation of the reactor

In order to survey and prove the performance of TRIGA 14MW LEU fuel, a program of measurements and comparisons, using previous results of HEU and Mixed Core, is performed over the entire converted core

Technical Objectives of Conversion

Requirements:

- Number of LEU fuel assemblies in core: 29;
- Fulfill the initial concept of core design to have one-side-drive, containing control rods and another side experimental vertical irradiation channels;
- Reactivity of bank control rods roughly equal to the double of core reactivity, to ensure flat power distribution;
- To satisfy the criteria of safe shutdown with most effective control rod blocked out of core;
- Maximum temperature in fuel rods (central temperature) should remain within the limits of the previously approved value at full power (14 MW);
- To ensure a sufficient number of in-core vertical irradiation places in order to increase availability and utilization;
- To demonstrate practical results of the entire program related to TRIGA-14MW core conversion, starting with initial design, analysis and first fabrication of LEU-TRIGA fuel until full conversion of the core, which will result in fitness for fuel service in agreement with the utilization program maximum burnup / less spent fuel and “0” cladding defects;
- To provide input for the qualification of fuel for storage

Technical Objectives of Conversion

K	J	I	H	G	F	E	D	C	B	A	
D	D	D	D	D	D	D	D	D	D	D	*12*
R	R	R	R	R	R	R	R	R	D	D	*11*
R	R	R	CR8	C_9	CR7	F_{50}	R	R	D	D	*10*
R	R	F_{51}	L_{38}		L_{42}	F_{52}	F_{53}	R	D	D	*9*
R	R	CR4	L_{61}	CR2	L_9	L_{44}	C_5	R	D	D	*8*
R	R	L_{49}	L_{24}	A	L_5	L_{46}	L_{54}	R	D	D	*7*
R	R	L_{32}	L_8	L_2	L_{45}	C_2		R	D	D	*6*
R	R	CR1	L_{60}	CR3	L_{62}	L_{47}	L_{55}	R	D	D	*5*
R	R	F_{56}	F_{57}	L_{40}	L_{39}	Ir	F_{58}	R	D	D	*4*
R	R	R	CR6	F_{59}	CR5	F_{60}	R	R	D	D	*3*
R	R	R	R	R	R	R	R	R	D	D	*2*
D	D	D	D	D	D	D	D	D	D	D	*1*

Fully converted core

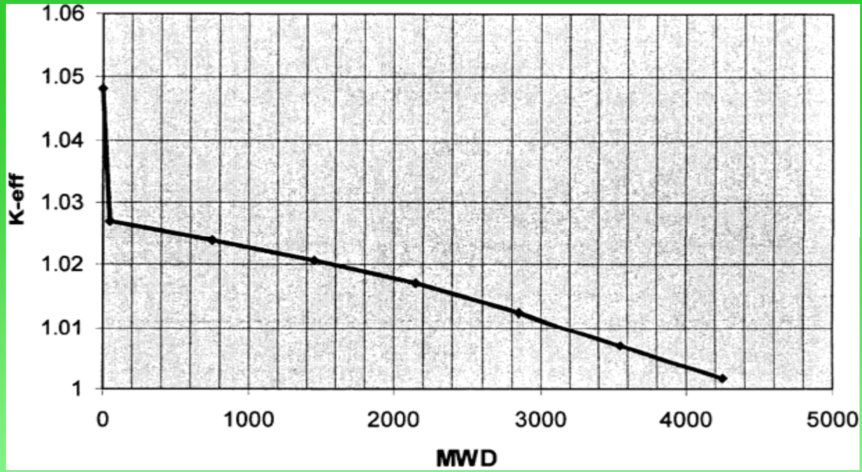
R = *Beryllium Reflectors*
D = *Aluminum plug*
L_n = *LEU fuel assemblies*
F_n = *Fresh LEU fuel assemblies (delivered by CERCA)*
CR1-8 = *Control Rods*
A, $C_{2,\ 5,\ 9}$, Ir = *Experimental channels*

Results of TRIGA-LEU core analysis and neutron flux determination at low power (2 MW)

- Analysis of core physics provides a design of 29 fuel assemblies with a higher reactivity, using only fresh LEU
- Due to the gradual conversion of the core, started in 1992, some 60% of fuel assemblies record an average burnup of 35%.
- For the LEU fuel supplied by CERCA – France for full conversion
  - *11 fresh fuel assemblies were selected*
  - *fresh fuel was located at the periphery of core fuel assemblies*
  - *prompt temperature coefficient of reactivity computed for the fully converted core is 10% higher than for HEU core at the beginning of the fresh core life*
  - *delayed neutron fractions β in the instances presented above are practically identical differences: below 1%*

Results of TRIGA-LEU core analysis and neutron flux determination at low power (2 MW)

- **Power peaking factors are identified in each fuel pin by using tri-dimensional DFA computer code and POW for proper selection of instrumented fuel pins location in core the maximum *power peaking factor value is 2.127***
- **fuel centerline temperature are determined by using PARET**
  - ***he maximum temperature in fuel center is 617ºC and clad 114ºC at 14MW power***
  - ***Lifetime of the designed core configuration will be 2 to 2.5 years for a utilization of 5500 hours/year***
  - ***forecasted refueling may occur at the beginning of 2009 with 2 or 3 fuel assemblies***



First LEU core lifetime

Thermo hydraulic Analysis

- The configuration of the converted core with LEU fuel is similar to the configuration of the initial designed HEU core, in terms of number of fuel assemblies, number of control rods, geometrical dimension of fuel assemblies and fuel pins, pitch, designed flow, coolant channels and water temperature.
- Some of the features are still different between these types of fuel concerning fuel “density” (specific weight), thermal capacity and thermal conductivity of material.
- The RELAP5 computer code was extensively used for transient analysis concerning Loss of Flow Accident (LOFA) and Reactivity Insertion Accident (RIA).

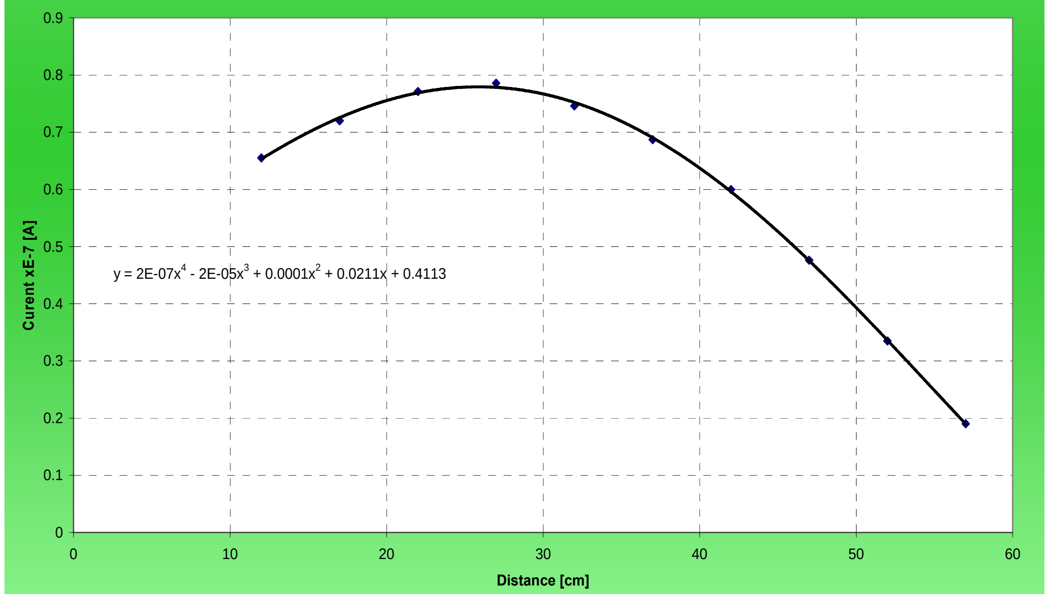
Thermo hydraulic Analysis

- **LOFA results, considering main pumps and emergency pumps shutdown, do not necessarily present differences between HEU and LEU and the natural convection mechanism of residual heat removal is safe to prevent any fuel and clad temperature increase**
- **RIA results, considering typical accident of TRIGA-14MW Safety Analysis Report initial power 1W, reactivity insertion 1% in 0.3 seconds for fresh cold core.**

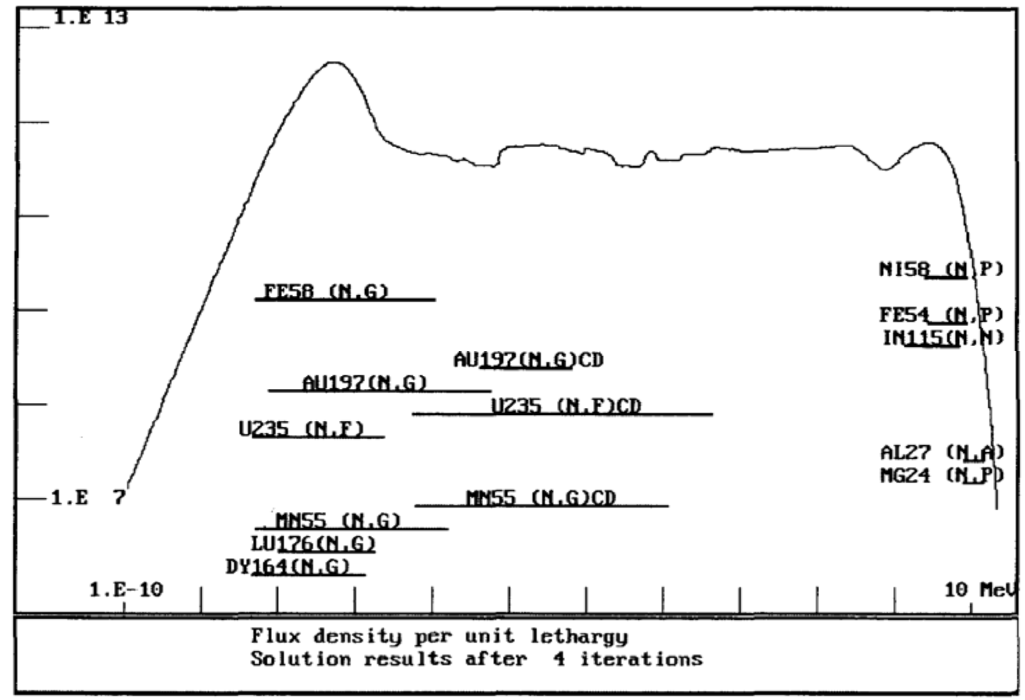
The behavior of LEU reactor core presents a peak power of 230 MW and a fuel temperature of 286ºC in comparison to HEU fuel, where power peak is 550 MW at a fuel temperature of 810ºC. The difference is determined by prompt temperature coefficient of reactivity, higher for LEU fuel and with better performances in this case of LEU.

Neutron Flux Determination at Low Power

- **The most controversial penalty of research reactor core conversion concerns the neutron flux in some reference in-core locations, where analytical determinations and previous measurements in HEU core or mix core were performed and considered as reference**



Axial thermal neutron flux distribution, P=1MW



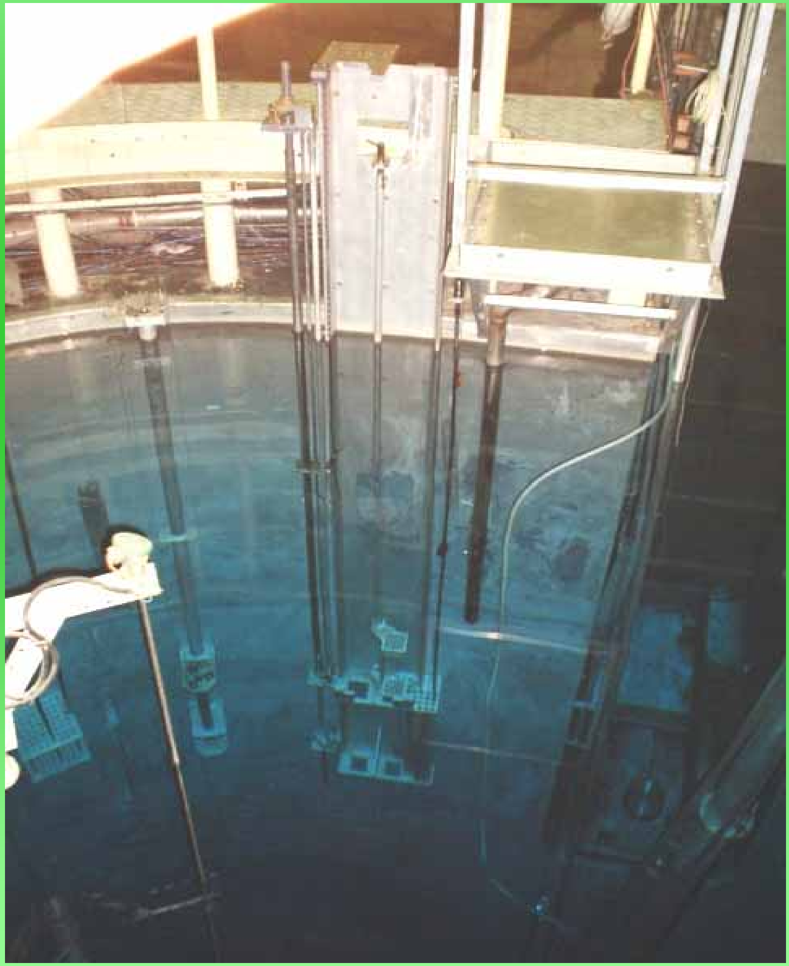
The differential and integral spectrum output of SAND2 code

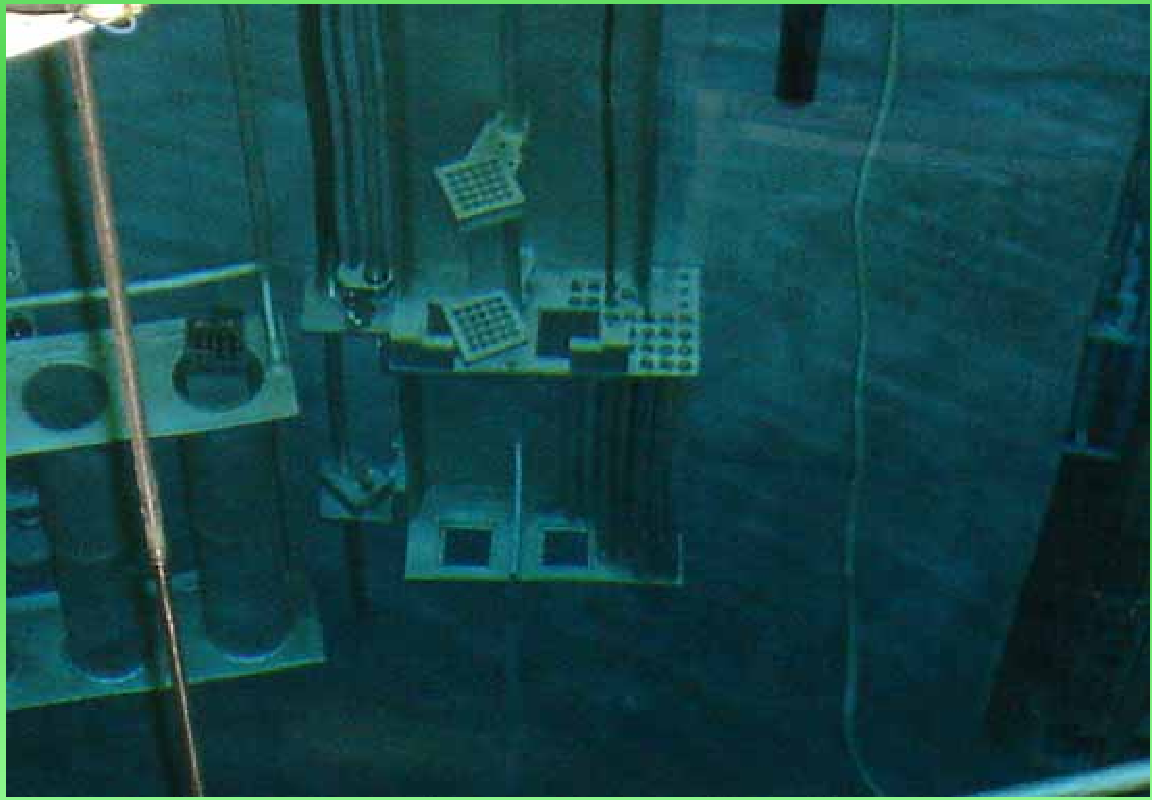
Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

- The behavior of TRIGA-LEU fuel during expected long duty cycle, more than 15 years in-core, accumulating a high burnup, over 43% of the initial U235 with a large number of power cycles (350-500), is difficult to be assessed by analysis and simulation
- 3 batches of LEU fuel are utilized, 2 batches manufactured by General Atomics and one (fresh fuel) manufactured by CERCA – France
- The references for LEU fuel behavior are the result of previous HEU utilization

Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

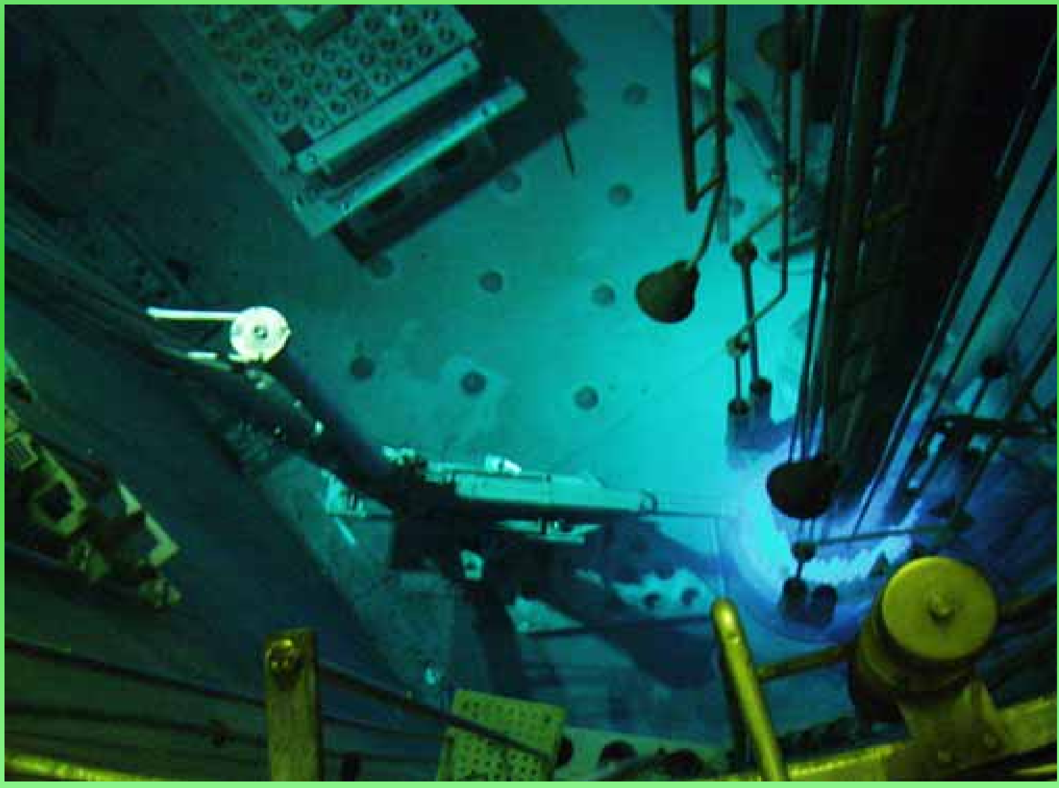
- **The permanently installed pool-side devices allow a rough control of all fuel rods elongation, bending as well as visual inspection.**

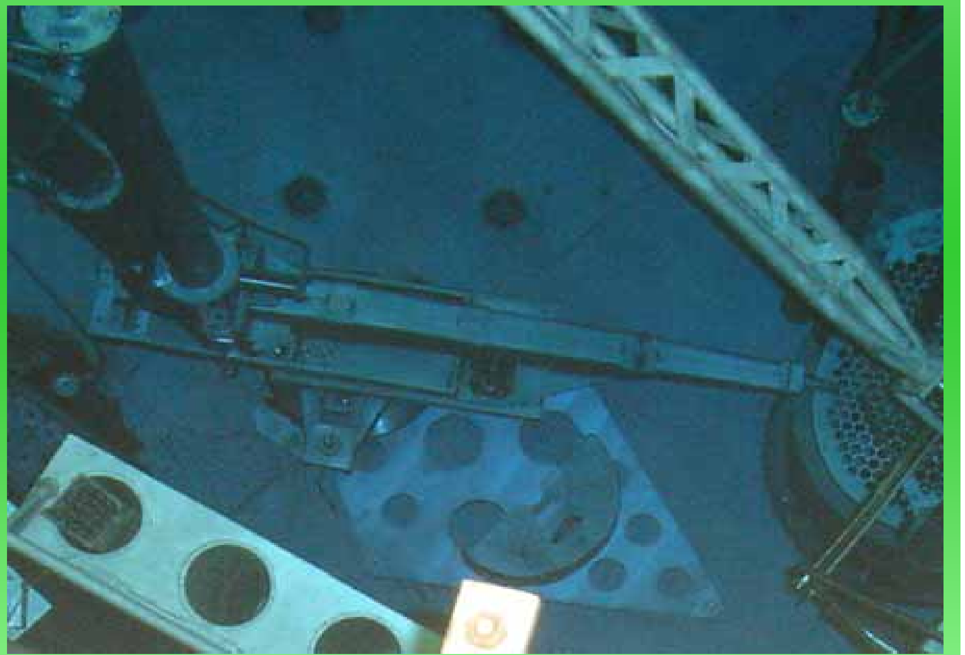




Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

- **The permanently installed under-water neutron radiography facility allows radiographic inspection of some selected fuel rods.**





Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

- The under-water gamma scanning (temporarily installed) allows burnup determination of each fuel rod in inspection campaigns, to confirm the in-core analytical power distribution, to produce a large set of information for fuel management, with results in fuel economy and safety, and also allows the spent fuel qualification before packing and shipment to the country of origin.

Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

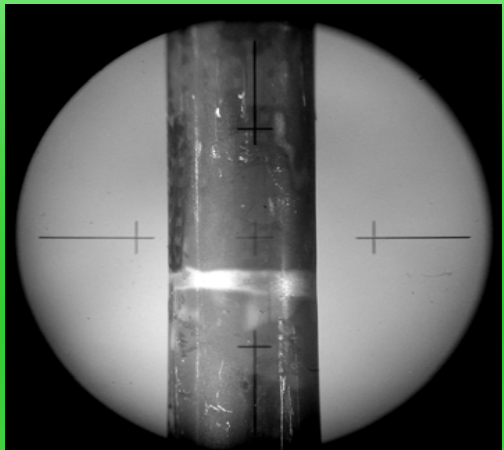
- The post-irradiation laboratory allows a highly accurate examination of LEU fuel by non-destructive and destructive examination, as follows:
  - direct visual inspection, through magnifying periscope, with digital photography;
  - profilometry of fuel elements, diametral increase, ovality, local asymmetry, swelling, bending, axial relative data distribution;

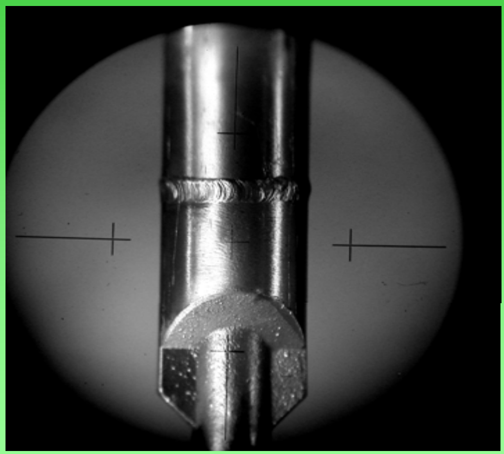
Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

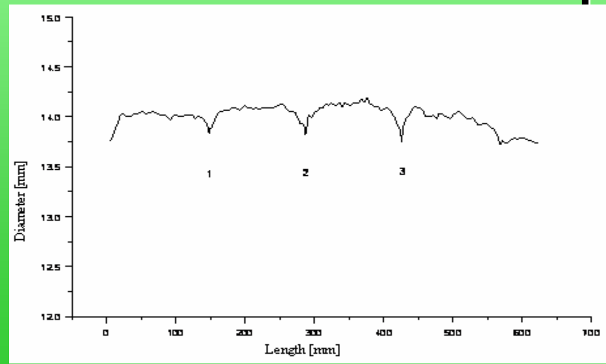
- gamma scanning and tomography: burnup axial distribution, peaking factors;
- destructive examination, plenum pressure on composition, metallography of fuel cladding, mechanical properties of cladding

Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

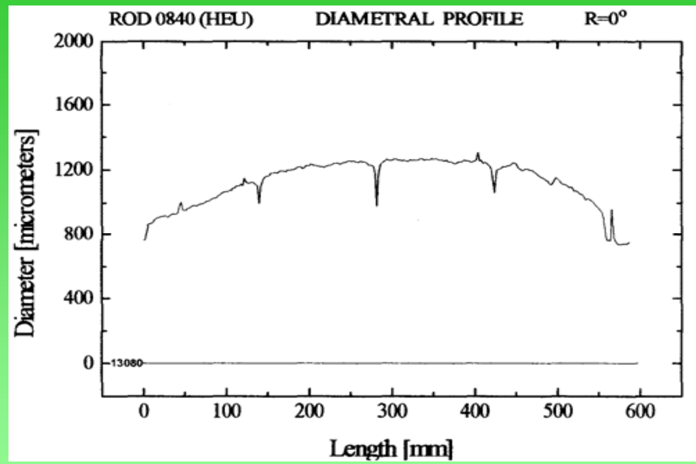
- From the first batch of LEU fuel 18 fuel elements have been selected for periodic examination







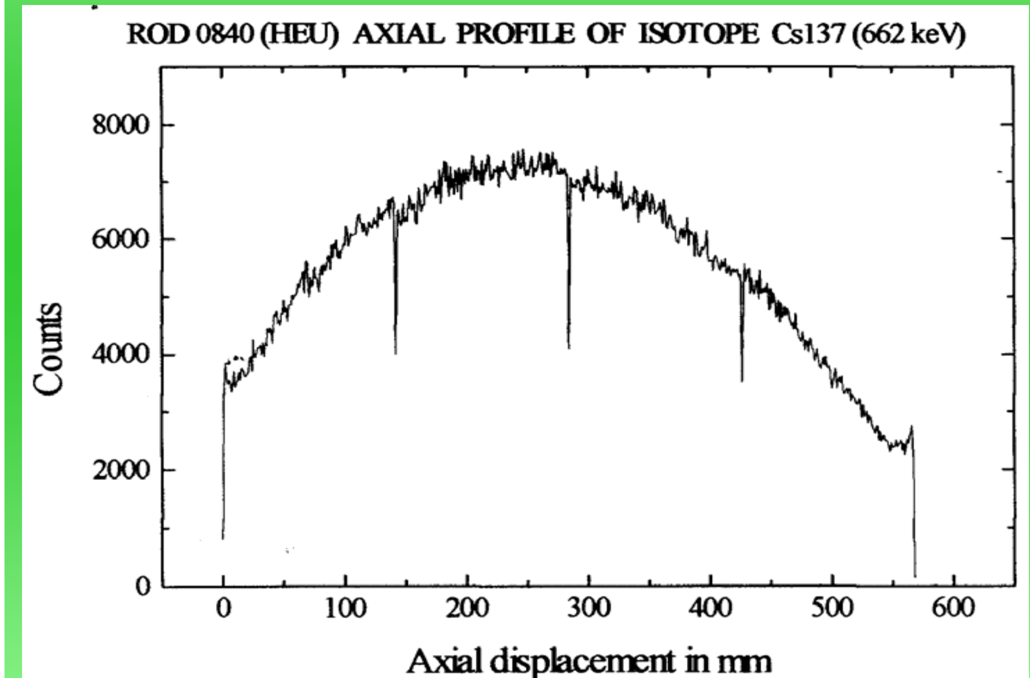
Distribution of values of the mean diameter along the fuel rod - LEU



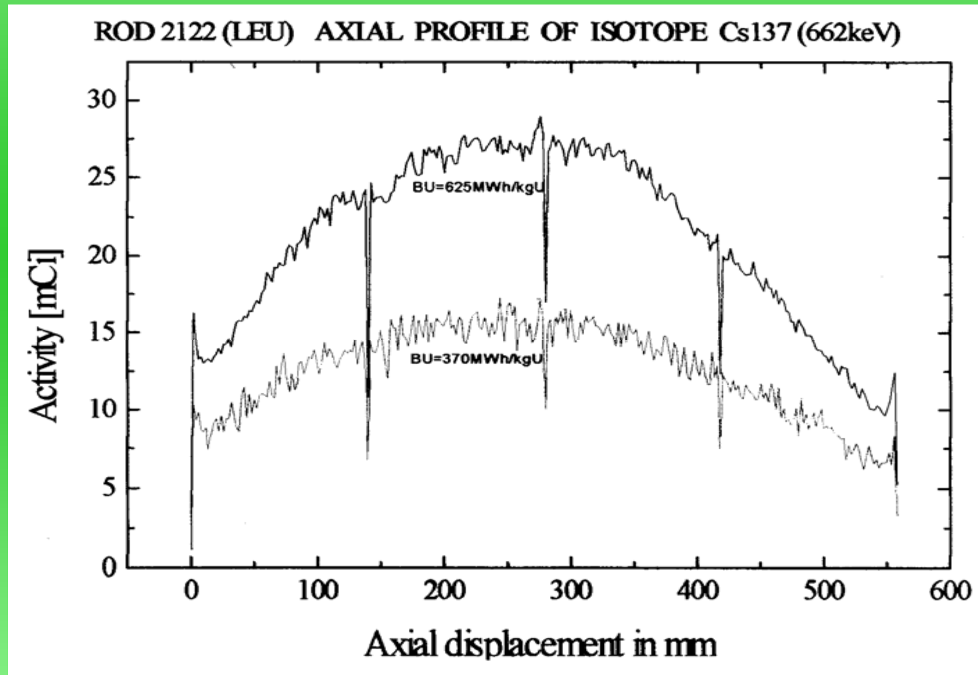
Distribution of values of the mean diameter along the fuel rod - HEU

Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

- For long term measurement and comparison the fission product Cs-137 was selected to avoid the incertitude produced by accumulation and decay of other fission products



Axial profile of gamma activity for Cs137 in HEU fuel rods

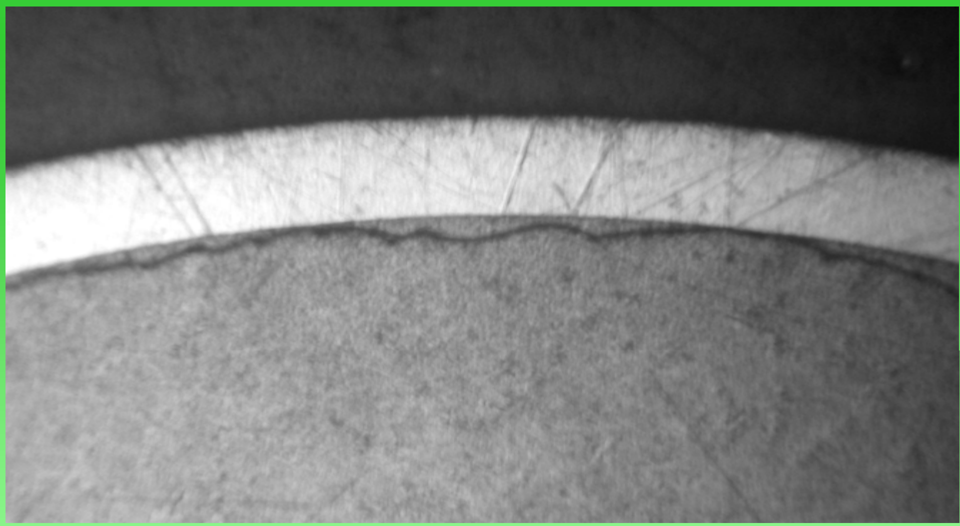


Axial profile of gamma activity for Cs137 in LEU fuel rods

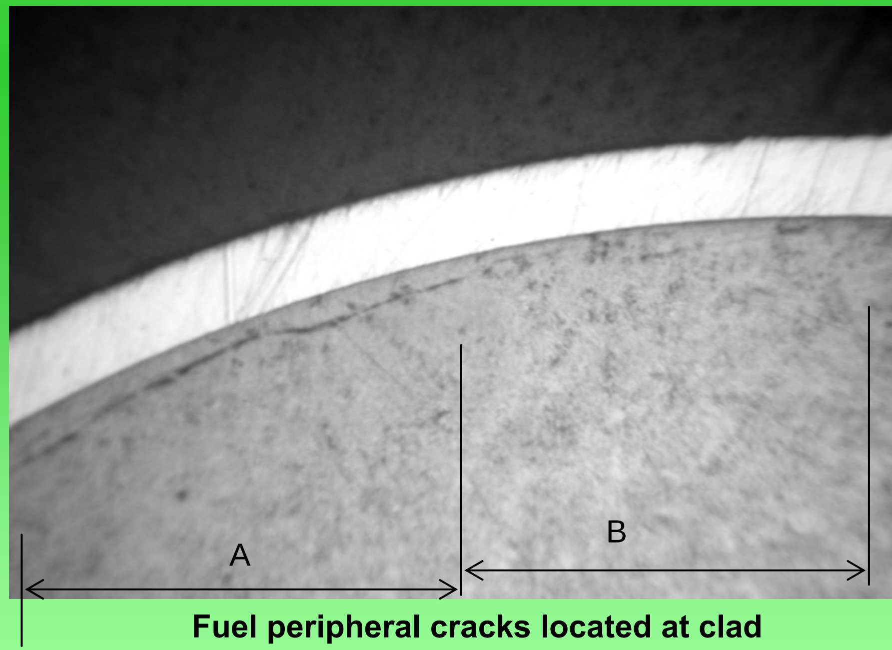
Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

Destructive examination of LEU fuel

- The circumferential cracks located at clad proximity can be associated with specific volume transformation due to phase modification or a high stress area produced by temperature gradient
- The difference is that uranium thickness in HEU fuel is 1µm and 5 µm in LEU fuel, producing a quasi-continuous uranium matrix
- Above 330ºC this matrix allows the transport of hydrogen from the high temperature area inside the fuel rod to the lower temperature



Fuel cracks located at clad proximity - *detail*

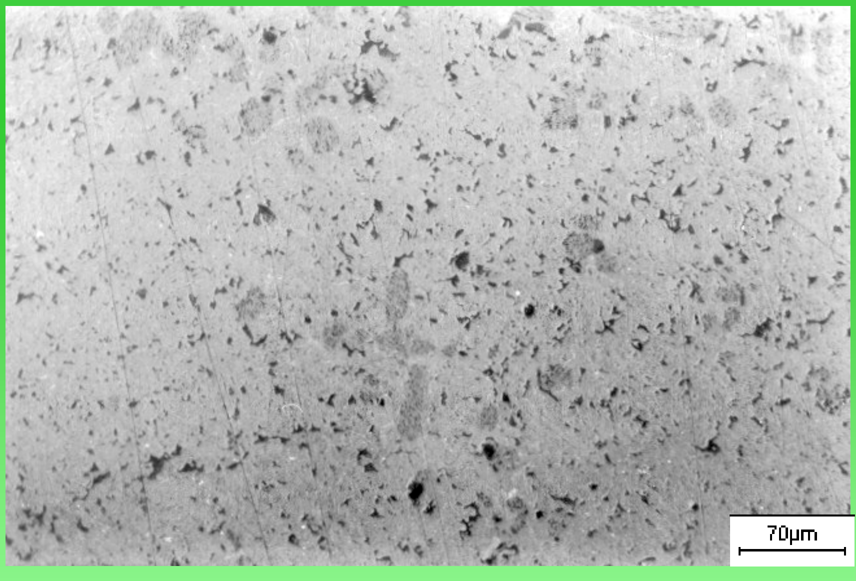


Fuel peripheral cracks located at clad proximity 1/3 of circumference

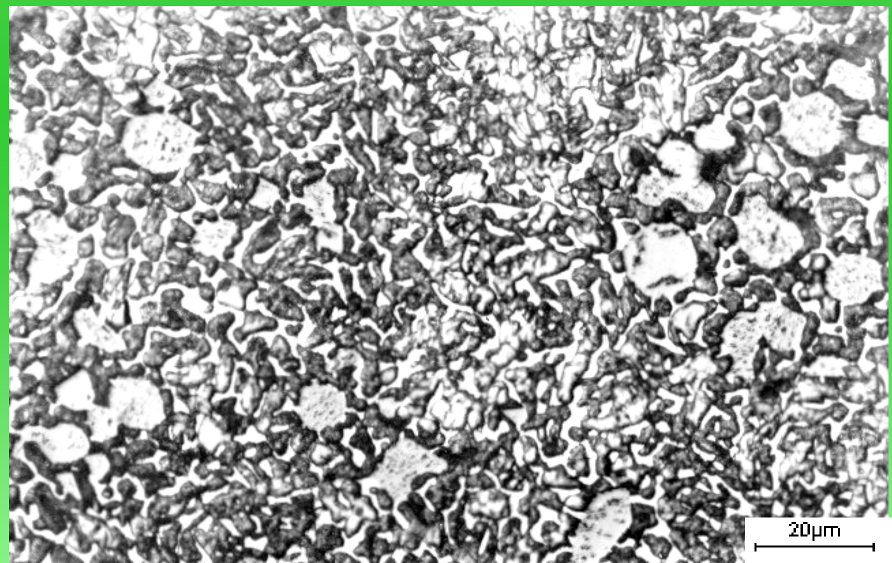
Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

Destructive examination of LEU fuel

- The microstructure of a central area is representative for metallic alloy operating at high burnup and high temperature, the micro-pores accommodating the fission products.
- The fuel structure is not affected by normal porosity. An etched metallographic sample shows the internal micro-structure of delta-phase of zirconium hydride and a fine alpha structure of uranium dispersion.



Micro-pores accommodating the fission products for metallic alloy operating at high burnup and high temperature

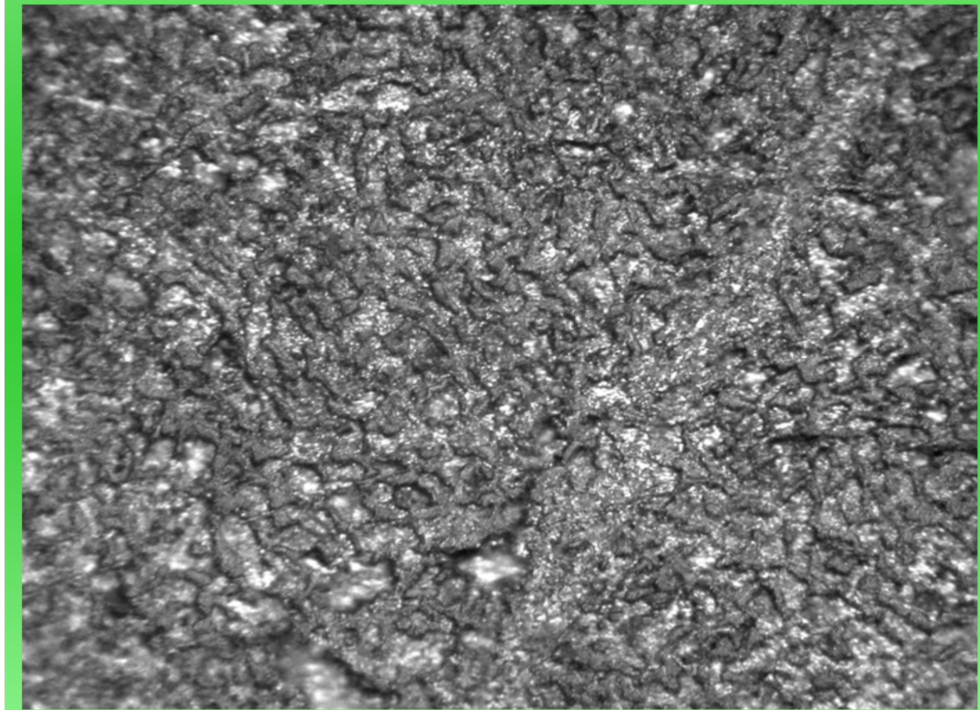


The delta phase of zirconium hydride and fine alpha structure at the edge of pellet

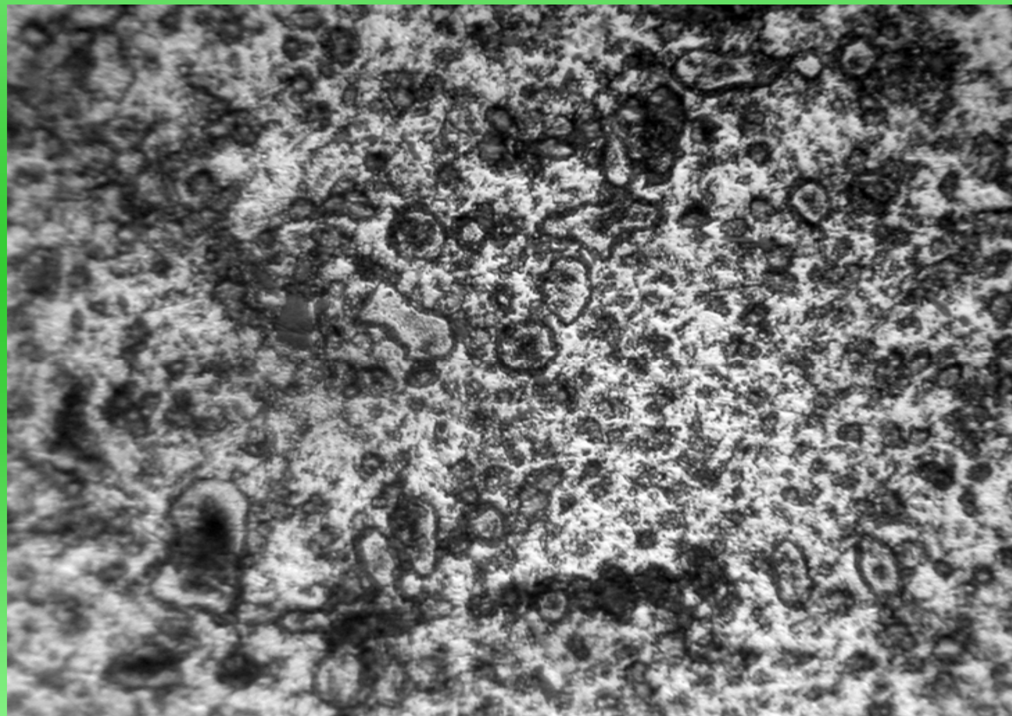
Continuous Evaluation of TRIGA-LEU Fuel Behavior during Irradiation

Destructive examination of LEU fuel

- **Some non-homogeneities are recognized at pellets edge where, due to fast cooling during pellets manufacturing, some of zirconium is not completely melted or is segregated.**



TRIGA LEU fuel structure (x100)



Peripheral TRIGA LEU fuel structure (x100) – non homogenous distribution of zirconium

Conclusions:

- **The conversion of the 14MW TRIGA reactor core was successfully accomplished throughout a relatively long period of time.**
- **The gradual conversion allows the accumulation of a large amount of experimental data which, to some extent, prove and confirm the results of previous analyses which funded the conversion.**
- **A careful approach of full converted core, based on continuous evaluation of analysis and experimental data, will allow the progressive increase of power and reactor operation, with demonstrated safety margins in terms of operation and fuel behavior**