VOLUME 240 (5) MAY 2010 ISSN 0029-5493

Nuclear Engineering and Design

An International Journal devoted to all aspects of Nuclear Fission Energy

CONTENTS

(Contents continued on back cover)

Available online at ScienceDirect www.sciencedirect.com

Affiliated with the European Nuclear Society (ENS) and with the International Association for Structural Mechanics in Reactor Technology, e.V. (IASMiRT)

Nuclear Engineering and Design 240 (2010) 1043–1049

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

TRIGA fuel burn-up calculations and its confirmation

R. Khan*, S. Karimzadeh, H. Böck

Vienna University of Technology (TU Wien)/Atominstitute (ATI), Stadionallee 2, A-1020, Vienna, Austria

ARTICLE INFO

Article history:
Received 16 November 2009
Received in revised form 6 January 2010
Accepted 13 January 2010

ABSTRACT

The Cesium (Cs-137) isotopic concentration due to irradiation of TRIGA Fuel Elements FE(s) is calculated and measured at the Atominstitute (ATI) of Vienna University of Technology (VUT). The Cs-137 isotope, as proved burn-up indicator, was applied to determine the burn-up of the TRIGA Mark II research reactor FE. This article presents the calculations and measurements of the Cs-137 isotope and its relevant burn-up of six selected Spent Fuel Elements SPE(s). High-resolution gamma-ray spectroscopy based non-destructive method is employed to measure spent fuel parameters. By the employment of this method, the axial distribution of Cesium-137 for six SPE(s) is measured, resulting in the axial burn-up profiles. Knowing the exact irradiation history and material isotopic inventory of an irradiated FE, six SPE(s) are selected for on-site gamma scanning using a special shielded scanning device developed at the ATI. This unique fuel inspection unit allows to scan each millimeter of the FE. For this purpose, each selected FE was transferred to the fuel inspection unit using the standard fuel transfer cask. Each FE was scanned at a scale of 1 cm of its active length and the Cs-137 activity was determined as proved burn-up indicator. The measuring system consists of a high-purity germanium detector (HPGe) together with suitable fast electronics and on-line PC data acquisition module. The absolute activity of each centimeter of the FE was measured and compared with reactor physics calculations. The ORIGEN2, a one-group depletion and radioactive decay computer code, was applied to calculate the activity of the Cs-137 and the burn-up of selected SPE. The deviation between calculations and measurements was in range from 0.82% to 12.64%.

1. Introduction

The Atominstitut operates a TRIGA Mark II research reactor since March 1962 with a thermal power of 250 kW. Its main task is to keep nuclear education and training alive in the fields of neutron, solid state physics, nuclear technology, reactor safety, radiochemistry, radiation protection, dosimetry, low temperature physics and fusion research. The ATI TRIGA Mark II research reactor utilizes solid fuel in which the zirconium hydride moderator is homogeneously mixed. The prompt negative coefficient is the unique feature of these fuel moderator elements which provide inherent safety by automatically limiting the reactor power to a safe level in the event of a power excursion. The reactor core consists of a lattice of cylindrical fuel moderator elements and graphite (dummy) elements. In each FE, the fuel meat is sandwiched between two graphite end sections that form the top and bottom reflector. An annular graphite reflector surrounds the core which is supported by an aluminium table at the bottom of the tank.

The TRIGA Mark II core can be observed through 5–8 m vertical water shield. Graphite thermal column and radiographic collimator are on opposite of the core and extend from the outer face of the reflector assembly into the concrete shield structure. Horizontal access and shielding for the thermal column are provided by a track-mounted heavy concrete door. A pool irradiation facility (bulk-shielding experimental tank) 9 ft (2.74 m) long, 8 ft (2.44 m) wide and 12 ft (3.66 m) deep provides shielding and access to the surface of collimator (GA, 1964). Four beam ports extend from reactor assembly through the water and concrete to the outer face of the shield structure.

The current TRIGA core is a mixed core of three different types of FE(s) i.e. aluminium clad (or 102-type), stainless steel clad (or 104-type) and FLIP (or 110-type) FE(s). The FLIP (Fuel Life Improvement Program) fuel uses 70% enriched uranium and has stainless steel cladding (Khan et al., 2009). The current core loading is 83 FE(s) with 54 elements of 102-type, 20 of 104 types and remaining 9 FE are FLIP FE(s) (Khan et al., 2009). Details' specification of these different fuel types is given in Table 1.

In this work, six spent 102-type FE(s) with fuel ID nos. 2156, 2196, 2077, 2124, 2184 and 2176 were selected for ORIGEN2.2 calculation and gamma spectroscopic measurements. A schematic diagram of aluminium clad FE is shown in Fig. 1. All these FE(s) were reshuffled during their irradiation history except FE no. 2196 which was placed in one fixed position during its whole irradiation period (Reactor log books, 1962–2009).

* Corresponding author.
E-mail address: rustamzia@yahoo.com (R. Khan).

0029-5493/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.nucengdes.2010.01.009

Table 1
Fuel element specifications of TRIGA Mark II research reactor of Vienna.

FE type	102-type	104-type	110-type
Fuel moderator material	U-$ZrH_{1.0}$	U-$ZrH_{1.65}$	U-$ZrH_{1.65}$
Uranium content (wt. %)	8.5	8.5	8.5
Enrichment (%)	20	20	70
Average ^{235}U content (g)	38	38	136
Diameter of fuel meat	35.8 mm	36.3 mm	36.3 mm
Length of fuel meat	35.6 cm	38.1 cm	38.1 cm
Upper graphite reflector	10.2 cm	6.8 cm	6.8 cm
Lower graphite reflector	10.2 cm	9.3 cm	9.3 cm
Cladding material	Al-1100F	304 SS	304 SS
Cladding thickness	0.76 mm	0.51 mm	0.51 mm

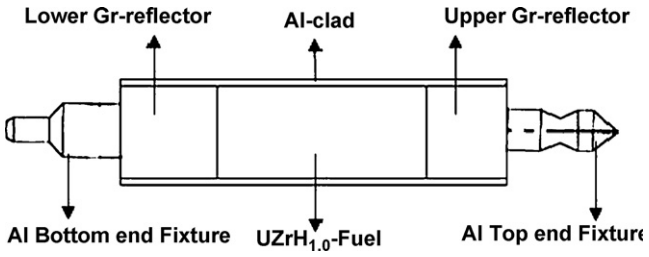

Fig. 1. Schematic diagram of an aluminium clad (102-type) FE.

The burn-up (BU) indicates the useful lifetime of the fuel in the reactor core. BU is a measure of the total amount of thermal energy generated per unit quantity of heavy element (U) charged to the core. Usually burn-up is expressed in MWd (kg U) (Matsson and Grapengiesser, 1997). The actual burn-up of the fuel in a reactor is determined by the physical and mechanical changes resulting from irradiation and high temperature in the fuel and the cladding, and also by the decrease in reactivity due to the decrease in fissile material and the accumulation of fission product poisons (Matsson and Grapengiesser, 1997).

The BU and its relevant nuclide composition of an irradiated fuel are usually needed for reactor fuel management, criticality safety, when dealing with SPE and validation of reactor physics calculations. Among several non-destructive testing (NDT) techniques, gamma spectrometry method is considered as to result in detailed information of the fuel irradiation history and the simplicity of measurement. Previous publications prove that the methods based on the activities of certain long-lived fission products are the most widely used (Wanga and Peir, 2000).

The selected SPE(s) were removed from the core and placed in cooling racks at different times (Table 2). Because of the long cooling time, most of the SPE have almost decayed their Cs-134 concentration. Therefore, this work concentrates only to determine the BU by Cs-137 determination. The TRIGA Mark II of Vienna operates at 250 kW and has very low burn-up, therefore at this very low consumption, it was determined by calculations that Cs-137 is almost proportional to burn-up. Moreover, it was also found in reference (Matsson and Grapengiesser, 1997) that the Cs-137 intensity is proportional to the burn-up. Therefore this work calculates the BU and confirms it through Cs-137 axial measurement.

The main efforts in this paper were focused on

- calculation of average burn-up and its relative isotopic composition of Cs-137 for six selected irradiated SPE(s) employing ORIGEN2.2 reactor physics code;
- confirmation of these calculations by the method of high-resolution gamma spectroscopy;
- axial burn-up redistribution applying gamma spectrometric measurements.

Table 2
Loading, reshuffling, removal and discharge from the core details of selected SPE(s).

FE no.	Action	Date	Position
	Loaded to core	09-03-1962	D15
2124	Remove from core	06-08-1985	Out from core
	Reloaded to core	17-10-1985	D15
	Remove from core	29-11-1985	Out from core
	Reloaded to core	21-11-1991	F06
	Discharged from core	04-03-1995	Out from core
	Loaded to core	09-03-1962	D02
2176	Remove from core	07-08-1985	Out from core
	Reloaded to core	11-10-1985	D02
	Remove from core	09-02-1999	Out from core
	Reloaded to core	04-12-2000	F25
	Discharged from core	08-02-2001	Out from core
	Loaded to core	09-03-1962	E20
2184	Shuffled	25-04-1974	C11
	Remove from core	06-08-85	Out from core
	Reloaded to core	12-10-1985	D16
	Discharged from core	08-02-1997	Out from core
2156	Loaded to core	09-03-1962	C7
	Shuffled	25-05-1974	E11
	Remove from core	09-01-1982	Out
	Reloaded to core	11-06-1987	F01
	Discharged	12-06-1987	Out from core
2077	Loaded	09-03-1962	E14
	Remove	06-09-1968	Out
	Reloaded to core	08-05-1973	B03
	Shuffled	24-05-1974	E09
	Discharged from core	04-08-1979	Out from core
2196	Loaded	09-03-1962	B04
	Discharged from core	08-08-1970	Out from core

The gamma scanning method was carried out for selected SPE(s) of TRIGA Mark II research reactor of the ATI, Vienna. These SFE(s) were loaded to the core on the same date while reshuffled and removed from the core differently. The details of loading, reshuffling, and removal from the core are given in Table 2 (Reactor log books, 1962 to 2001).

The TRIGA core is a cylindrical lattice in which FE(s) are arranged into five circular rings B–F) around the central irradiation channel 'A'. The top view is shown in Fig. 2 where 'A' is central the irradiation channel while ring B–F rings have different positions for reactor core components.

Using the log book records, Full Power Days (FPD), the Full Operating Length (FOL) in days and power at FOL in MW were calculated and applied as input to the selected reactor physics code. The irradiation history in terms of FOL and average power (MW_{Th}) at FOL of each SFE is shown in Fig. 3. For example, in Fig. 3, the FE no. 2196 was irradiated on power 6.879×10^{-5} MW for first 872 full length operating days of irradiation and its power was raised to 3.629×10^{-3} MW for next 2202 days of irradiation. The dotted line shows the weighted average power 3.4773×10^{-4} MW of both power levels. The irradiation history of FE 2196 is given in Table 3. The same scheme is applied to all other SPE(s).

Table 3
Irradiation history calculation of FE no. 2196 from log books.

From	To	FOL (days)	MWd	FPD	P (MW)	FLP (MW)
07-03-1962	27-07-1964	872	4-13	41.3	1.456×10^{-3}	6.879×10^{-5}
28-07-1964	07-08-1970	2202	69.504	278.0	3.629×10^{-3}	4.582×10^{-4}
08-08-1970	06-11-2208	13,971	Decay time until date of measurement			

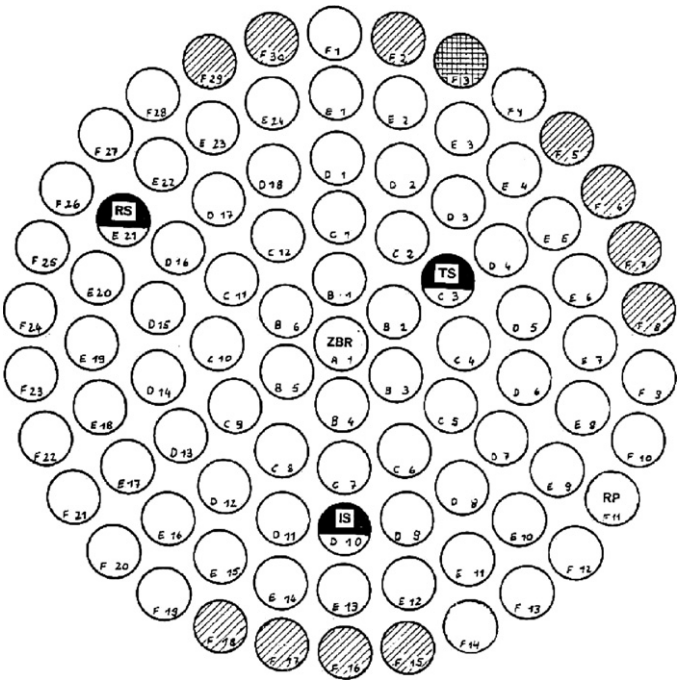

Fig. 2. Core configuration with rod locations labeled.

This series of measurement was carried out for the same type of FE(s) i.e. 102-type fuel. The only difference was their individual irradiation histories and resulting burn-up. The accuracy of the ORIGEN2 BU model for each FE depends on its location in the core, number of reshufflings and the precision of operational records from log books. Keeping these factors of accuracy in view, the FE 2196 was identified with the simplest irradiation history because it was placed and kept only in one position and finally removed from the core without any reshuffling. The same element was also used as reference element during BU calculation by reactivity method (Ravnik et al., 1992).

The current Cs-137 radioactivity of each element was calculated using ORIGEN2 under their given irradiation conditions of the reactor log books while the same FE(s) were measured by gamma spectroscopy. For each FE, these measurements were performed at scale of 1 cm. The measurement results were found close to calculated results, confirming the ORIGEN2 model for BU and isotopic composition computation of TRIGA burned fuel.

2. Methodology

2.1. Gamma spectroscopy

The gamma spectroscopic measurements were performed in the reactor hall of ATI but outside the reactor tank. More than adequate shielding was provided to the system by the high density lead fuel transfer cask and fixtures of the fuel inspection unit. About 2–3 μSv dose rate was recorded at the contact surface of the cask and working station. The experimental setup which consists of the fuel transfer cask, the inspection unit, beam collimator and coaxial high-purity germanium p-type detector (HPGe), is shown in Figs. 4 and 5.

The FE to be measured was mounted to the fuel inspection unit through fuel transfer cask where it can be moved vertically with an adjustable speed. Although this unique fuel elevator system has an ability to scan each millimeter of the SPE accurately in axial direction however, only, 1-cm steps were selected for each measurement. To avoid any overloading of the gamma spectrometer, the collimator of 1 cm diameter was used and the distance between detector and fuel rod was kept about 10 cm. To minimize the statistical and counting errors, the time for each measurement was selected 300 s. The dead time of the detector was kept below 16%. The axial position of the rod to be scanned was indicated by a digital monitor fixed on the fuel inspection unit.

The signal from the detector is transferred to the on-line computer (PC) with calibrated gamma spectroscopic software. Using suitable fast electronics, 300 s was set to record the gamma-ray spectrum for each centimeter, the spectrum was saved on a removable hard disk of the PC for further detailed analysis i.e. identification of Cs-137 peak, corresponding peak area, etc. Fig. 6 illustrates one example of the typical plenum gamma-ray spectrum with Cs-137 peaks.

The counting errors were controlled up to 1.0% (in one standard deviation). The counting dead times were generally controlled to be ≤16% and were corrected during the counting period. The spectrum analysis provides the counts per second of Cs-137 (net peak area) which gives experimental activity using following relation (Wanga and Peir, 2000).

$$A_{\text{exp}} = \frac{C}{\varepsilon \times \gamma \times f} \tag{1}$$

where C = photo peak area (cps); ε = absolute efficiency; γ = gamma-ray branching ratio; f = fuel self attenuation factor.Self-shielding factor calculation

The self-shielding factor "f" in the above relation is incorporated to correct that fraction of gamma-rays, which are emitted from fission products (FPs), but not detected due to fuel self absorption. Under the given geometrical conditions, this factor is calculated according to the FP distribution and the gamma-ray attenuation coefficient of the fuel rod. Monte Carlo shielding code MCNP5 (Monte Carlo team, 2005) was applied to calculate this factor. For this purpose, a fuel scanning machine and fresh Al-clad FE were simulated by MCNP5 as shown in Fig. 7. In the simulation, a homogeneous distribution of Cs-137 was applied. The two calculations were performed i.e. flux-tally results with Cs-137 distribution and without Cs-137 inside the FE. The MCNP model for these both cases is shown in Fig. 7. The ratio of F2-tally results for both cases provided the value of self-shielding factor "f". In this case this factor was found as 15% of total Cs-137 emission.

2.2. Reactor physics calculations

The reactor physics code ORIGEN2 was chosen for activity and BU calculations, which can simulate the build up and decay of nuclides during irradiation. ORIGEN2 uses a matrix exponential method to solve a large system of coupled, linear, first-order ordinary differential equations with constant coefficients (Croff, 1999). The calculations for above mentioned FE(s) were performed using the ORIGEN2 reactor code. As all selected FE(s) have different irradiation history therefore each FE was calculated independently. Based upon full operation length, the irradiation history of each FE was divided into appropriate number of equal steps. The step length of each irradiation interval was set to 300 days. Weighted average power was applied to all irradiation steps. Irradiation power history of each element is shown in Fig. 3.

ORIGEN2 model for each spent FE was developed to calculate the average burn-up and its relevant material isotopic composition. This model needs following three main inputs for these calculations.

(1) Material inventory
(2) Library selection
(3) Fuel irradiation history

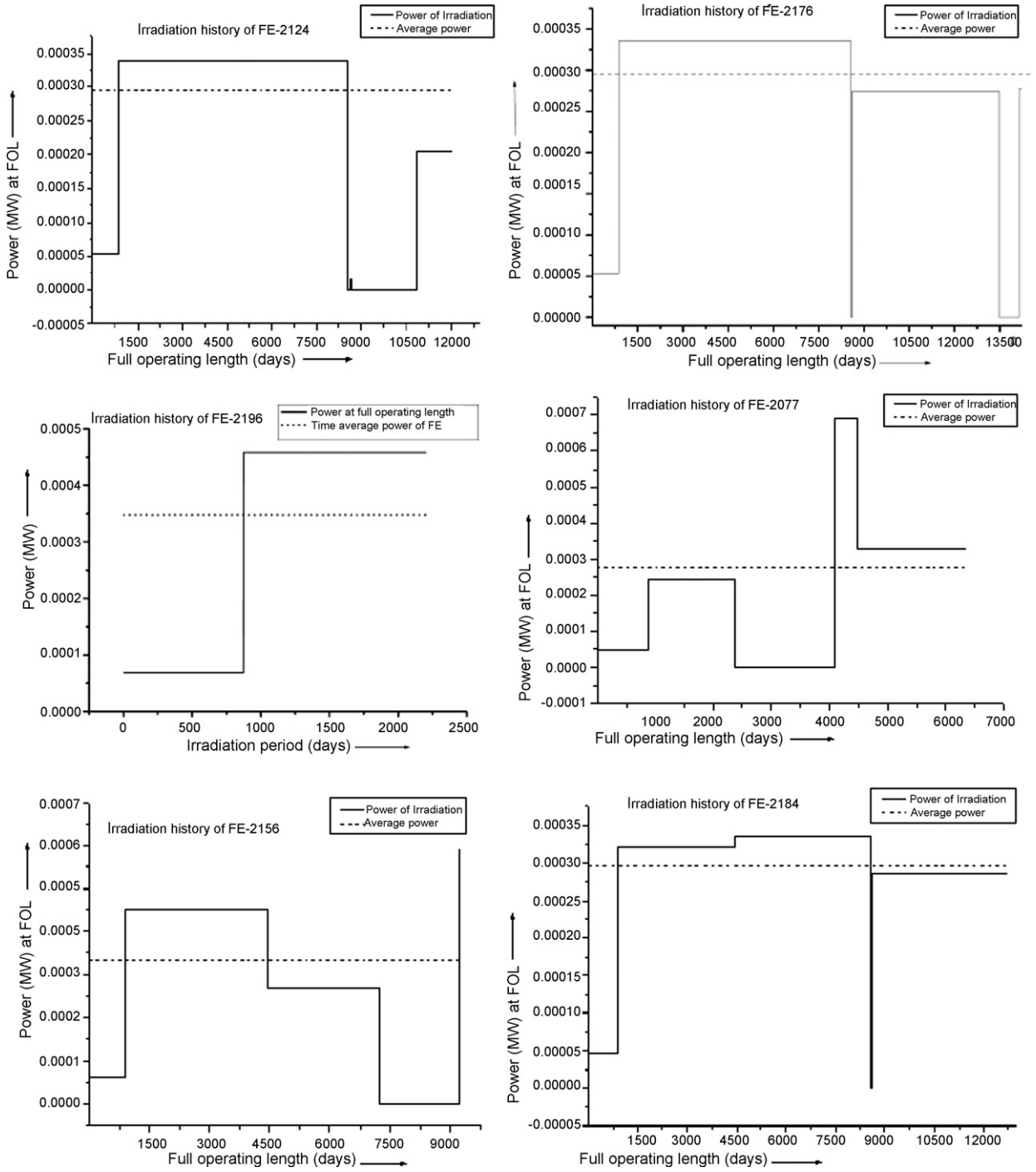

Fig. 3. Irradiation history of each SPE at full operating length (FOL).

Table 4
TRIGA Al-clad fuel composition (in gram) for ORIGEN2.2 calculations.

	FE: 2124	FE: 2176	FE: 2184	FE: 2156	FE: 2077	FE-2196
U-235	35.99	36.34	35.65	36.61	35.72	36.93
U-238	145.7	147.09	144.3	148.2	144.61	149.51
U-234, U-236[a]	0.37	0.37	0.37	0.37	0.37	0.37
Hydrogen[a]	22.46	22.46	22.46	22.46	22.46	22.46
Zirconium	2038.52	2038.96	2052.61	2038.32	2040.15	2042.76

[a] Average values, calculated from shipment documents.

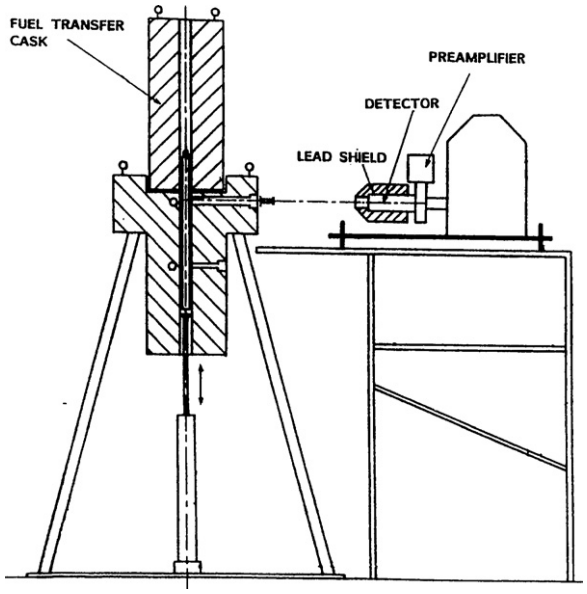

Fig. 4. Actual experimental set up developed at Atominstitte.

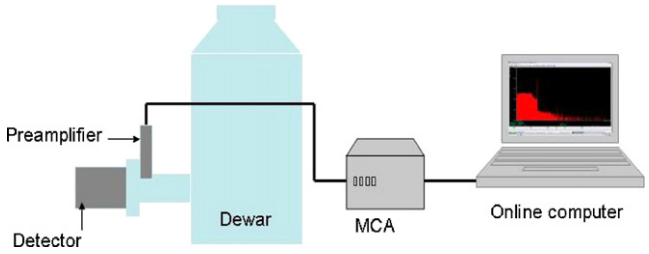

Fig. 5. The schematic diagram of experimental setup for gamma spectroscopy.

The material inventory of each SPE was taken from fuel shipment documents (GA, from 1962 to 1988). The material inventories, used in the model, are given in Table 4. Concerning library selection, ORIGEN2 is not equipped with TRGIA reactor library. Therefore on the basis of previous published work on this subject (Mele et al., 1990), the PWR library was found appropriate for TRIGA reactors and applied to this ORIGEN2 model. The fuel irradiation part of the model is of key importance because it plays role in the accuracy

Table 5
Power factors of TRIGA Mark II core.

Fuel ring	A	B	C	D	E	F	G
P_f	1.0	0.9	0.8	0.7	0.6	0.5	0.5

of the model. Reactor operation log books were used carefully to extract the accurate irradiation history of each FE.

2.2.1. Irradiation model

All described SPEs were calculated separately because of their different individual irradiation history. These elements were loaded to the core on the same date i.e. March 9, 1962 but in different ring positions. The history of their loading to core, their reshuffling in the core and discharge from the core is described in Table 2. Using total irradiation length and Megawatt hour (MWd) from the log books, the full operation length FOL (in days) was calculated for each SPE. Using irradiation power of each FE at specific location and FOL, the weighted average power of each SPE at FOL was calculated and applied to ORIGEN2 model. The basis of the calculation i.e. (MWd) for each SFE were taken from the log books (Reactor log books, 1962 to 2001) and corresponding power MW was distributed in the core using power factors described in Table 5 and Eq. (2). The total irradiation power in Eq. (2) was taken from log books. By incorporating the decay time of each SFE till the date of measurement, the burn-up and the radioactivity of each SPE was calculated. The results are given in next section.

$$P_{\text{irr}} = \frac{\text{Total Thermal Power}}{\text{Number of FE}} \times P_f \quad (2)$$

where "P_f" are power factors and are given in Table 5 for each ring or TRIGA reactor core.

3. Results and discussions

For each SPE, the calculated BU (MWh) and corresponding average activity (Bq) of Cs-137 for each centimeter are presented in Table 6. The graphical comparison of calculation and measurements is given in Fig. 8. The factors causing these deviations between calculations and measurements are being discussed in this section.

First, this TRIGA reactor is operating since 1974 with a mixed core of three different types of fuel. Most of these FE(s) were reshuffled during their long history therefore percent deviation between calculations and measurements vary from element to element depending on their individual irradiation histories and different

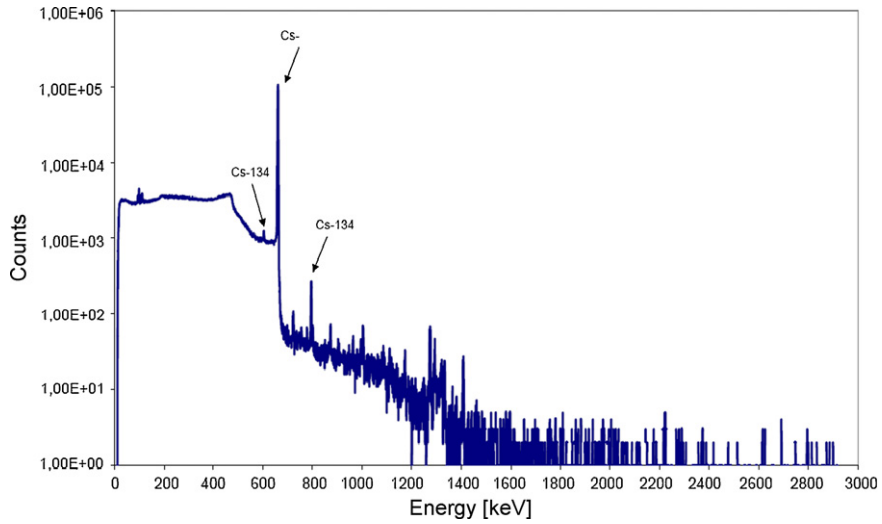

Fig. 6. The typical gamma spectrum of TRGA aluminium clad FE.

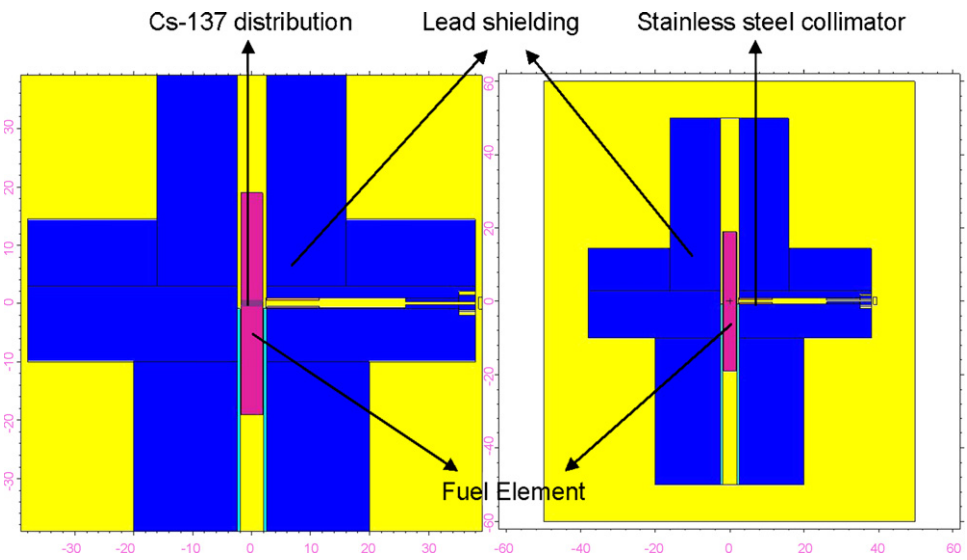

Fig. 7. The MCNP model employed for self-shielding factor "*f*" calculations.

Table 6
Comparison of ORIGEN2.2 calculations and spectroscopic measurements.

FE number	Burn-up (MWh)	Calculated Cs-37/cm	Measured Cs-137/cm	Percent (%) difference
2196	25.68	1.35E+09	1.36E+09	0.82
2077	30.92	1.72E+09	1.60E+09	6.87
2156	58.08	3.52E+09	3.60E+09	2.29
2124	69.24	4.59E+09	4.44E+09	3.21
2184	89.91	6.60E+09	7.09E+09	7.49
2176	95.56	7.22E+09	6.31E+09	12.64

positions in the core (Ravnik et al., 1992). Second, the basis of the calculation (i.e. MWD) was taken from log books and because of long history (since 1962); any documentation uncertainty in the log books may contribute to these variations. And the third, the PWR libraries of ORIGEN2 are applied to this SPE ORIGEN2 model which have very small but some contribution in these deviations. These percent differences between the calculations and measurements of the Cs-137 activity are reasonable and confirm that the corresponding burn-up calculations of selected SPE(s) are reliable.

The spectrometric analysis provides the Cs-137 axial distribution for given FE(s). As mentioned that the Cs-137 production and BU are proportional (Matsson and Grapengiesser, 1997) therefore applying this axial distribution of Cs-137, the relative axial burn-up distribution of each measured SPE can be calculated with reasonable accuracy. Employing its Cs-137 axial distribution, the relative axial BU distribution of SFE 2196 is shown in Fig. 9. Two slight peaks

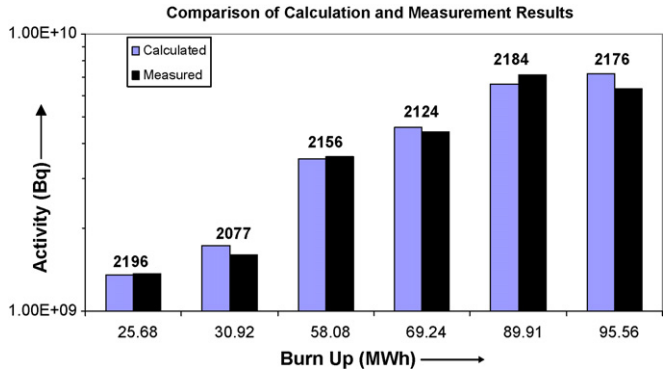

Fig. 8. Comparison between gamma spectroscopic measurements and ORIGEN2 results for six TRIGA SPE.

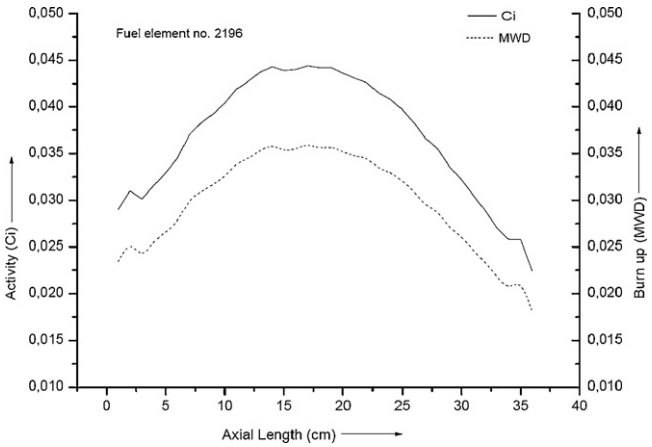

Fig. 9. The measured Cs-137 and relative axial burn-up distribution of FE 2196.

at both ends of the FE are due to the presence of two axial graphite reflectors as also shown in Fig. 1.

4. Conclusion and outlook

ORIGEN2 software with PWR library is an appropriate tool to calculate the burn-up and isotopic composition of TRGIA FE(s). Employing the Cs-137 axial distribution, the axial burn-up of the same FE can be calculated for each scanned segment of the FE. The high-resolution gamma spectroscopy technology that is developed is versatile measuring method. It provides rapid information about several processes taking place in the fuel meat with the possibility of feedback to operators. Further, using these experimental techniques along with reactor physics calculation tool, the distribution of burn-up along the length of fuel can be predicted.

This work is a part of PhD thesis at ATI. The confirmed ORIGEN2 model will be applied to all FE(s) present in the current core of the ATI reactor. The effective material composition will be applied to the MCNP model, developed at ATI, to perform the neutronics analysis of current the TRIGA reactor core.

References

Croff, A.G., 1999. A user's Manual for the ORIGEN2 Computer Code. OAK RIDGE National Laboratory, USA.

General Atomic (GA), 1964. TRIGA Mark II Reactor General Specifications and Description, March. General Atomic Company, U.S.A.

General Atomic (GA), from 1962 to 1988. The Fuel shipment documents of TRIGA Mark II of Vienna. Austria.

Khan, R., Karimzadeh, S., Boeck, H., 2009. TRIGA Fuel Burn-up Calculations Supported by Gamma Scanning. RRFM 2009, Vienna, Austria.

Matsson, Grapengiesser, B., 1997. Developments in gamma scanning of irradiated nuclear fuel. Appl. Radiat. Isotopes 48 (10–12), 1289–1298.

Mele, I., Slavic, S., Ravnik, M., Dimic, V., September 11–13, 1990. TRIGA Data Base for ORIGEN2". 11th TRIGA user conference. Heilderberg.

X-5Monte Carlo team, 2005. A general Monte Carlo N-particle transport code version 5. In: MCNP5 Manual. Los Alamos National Laboratory, U.S.A.

Ravnik, M., Strebl, M., Böck, H., Mele, I., 1992. Burn-up determination of TRIGA fuel elements by calculation and reactivity experiments. Kerntechnik 57 (5), S291.

Reactor Log books, from 1962 to 2001, of TRIGA Mark II reactor. Atominstitute, Vienna, Austria.

Wanga, Tien-Ko, Peir, Jinn-Jer, 2000. An iterative approach for TRIGA fuel burn-up determination using nondestructive gamma-ray spectrometry. Applied Radiation and Isotopes 52 (2000) 105 ± 118.