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Decommissioning Plan and Cost Estimation of TRICO-II Research Reactor

Beya. H[1], Rowayda F. Mahmoud[2], Ahmed El Saghir[3], M. K. Shaat*[2], and Alya Badawi[3]

[(1)] *Commissariat Général à l'Energie Atomique (CGEA)*
[(2)] *Egyptian Atomic Energy Authority*
[(3)] *Faculty of Engineering, Alexandria University, Egypt*

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ABSTRACT

Decommissioning is the final stage of the reactor lifetime. A preliminary decommissioning plan has been presented for TRIGA-II Research Reactor in the Democratic Republic of Congo (DRC). One of radiation protection requirements and environmental safety during the preliminary decommissioning plan is the database of the spent nuclear fuel activities and inventory of TRICO II operational history, that were calculated using MCNPX code to support the decision makers. The total activity for all spent fuel is 19.32 E+02 Ci, and the average value for each spent fuel element is about 27.603 Ci. The fissile nuclides produced in the depleted fuel were Pu-239, Pu-241 and U-233 with a total weight of about 4.0 gram. The cost estimate of the decommissioning of TRICO-II reactor was calculated using IAEA software CERREX code. The input inventories of the decommissioning activities were estimated, its output cost was about six million US dollars, which is in the range of cost estimation for similar TRIGA reactors. Moreover, the total amount of the radioactive waste generated from the decommissioning activities has been estimated to be about 806.5 tons of low-level radioactive waste, which can be managed with the waste disposal unit.

1. INTRODUCTION

Decommissioning is the final stage in the lifetime of a nuclear facility. The main purpose of decommissioning is to transfer the nuclear reactor to its end life state with the approval of the regulatory supervision and control [1-7].

The suitable budget for decommissioning is linked to the safety and protection of current and future generations from harmful effects of ionizing radiations. A sufficient financial fund should be established in advance to ensure that all decommissioning costs are included without causing future generations any harm[3]. The following international standards are used to decommission a nuclear facility in accordance with international standards [4-11]:

1) Immediate dismantling; in which the equipment, structures and parts of a facility containing radioactive waste are removed or decontaminated to a safe level that is approved by the regulatory body. In this case, decommissioning activities begin after the end of the facility operations.
2) Deferred dismantling; in which parts of a facility containing radioactive contaminants are either processed or placed in safe conditions until they can be decontaminated and dismantled.
3) Entombment; in which radioactive contaminants are encased in a structurally long-lived radio-nuclides until radioactivity decays to a safe level permitting the unrestricted release of the nuclear facility.

The safety assessment during decommissioning is required to ensure that the confinement of the radioactive nuclides, removal of the mechanical barriers and the control of the radiation level for the personnel and environment are performed according to ALARA principle. The success of the decommissioning plan depends on the calculation and assessment of the activities of the radio-nuclides and dose rates of the operational structures, components and spent nuclear fuel [8].

Corresponding author: m_shaat3073@yahoo.com
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2. Description of TRICO-II Research Reactor [9]

2.1 Reactor tank

The reactor tank, having a diameter of 1.98 m and a height of 7.5m, is filled with demineralized water, has. It is a waterproof aluminum cylinder serving as an octagonal massive inner wall of biological protection. At the median plane of the core, the tank has five horizontal geometric inward forms, corresponding to the thermal column and the four neutron beam extraction tubes. The inner wall of the reactor tank includes on both sides of the thermal column, eight vertical rails used to fasten different devices in particular:

- The supports of the detection chambers
- Arrival and departure piping to primary cooling circuits
- Two storage racks intended to receive any fuel element from the core
- Projectors for swimming pool lighting
- Different probes for water control (temperature, resistivity and level).

During normal reactor operation, two control rods are operational; the regulating rod (R) and the control rod (C), the other two rods (safety and pulsation) are kept out of the reactor core. The P rod is employed for performing the power pulses and as a safety rod during normal operation.

2.1.1 Reactor core:

The reactor core contains; nuclear fuel elements, reflector elements, a central channel, four control rods and the tubes of the pneumatic conveyor. The reactor maximum thermal power is 1000 kW in the steady state. This is equivalent to loading of 70 fuel elements, i.e., equivalent to a mass of 13.3 Kg of uranium including 2.63 Kg of U-235.

The core shape is a right cylinder 44.6 cm in diameter, delimited by two aluminum grid plates which provide accurate spacing between the fuel elements. Both grids have 90 symmetric holes distributed along 6 concentric rings which hold 1, 6, 12, 18, 24 and 30 locations. These locations are filled either with fuel elements or different core components like graphite elements, control rods, neutron sources and irradiation channels. The lower grid has 31 holes more than the upper one to facilitate the circulation of water. A 30 cm thick radial graphite reflector surrounds the core while the axial reflector is provided by the fuel element itself. The holes in the grid are loaded with reflector elements to ensure a better saving of the neutrons.

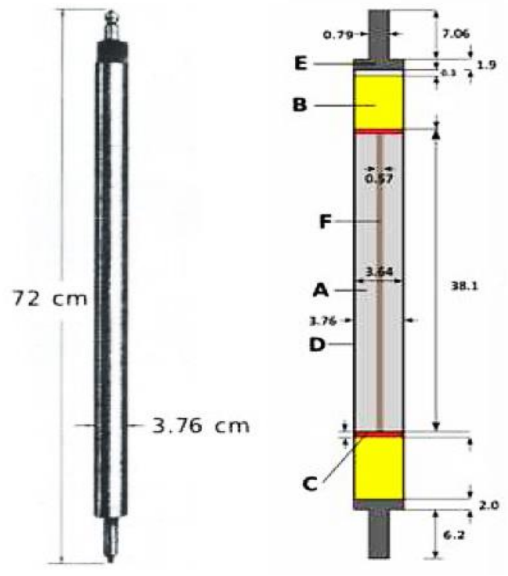

Fig. (1): The fuel element

2.1.2 Fuel element

TRICO-II reactor is loaded with the 104-type fuel elements which were manufactured by General Atomic. It uses the zirconium hydride with the atomic ratio of 1.65 (ZrH1.65) and two burnable poison disks (Sm_2O_3) [18]. The fuel itself is placed at the center [A], while the top and the bottom parts of the rod, made of graphite, play the role of axial neutron reflectors [B]. The burnable poison disks [C] are placed between the fuel and the axial reflector. Everything is contained in a stainless steel (0.051 cm thick) cladding [D] and two end caps with appropriate pins for positioning and moving the fuel elements [E]. There is a zirconium rod at the center of the fuel meat [F]. In ring B, there is a special instrumented FE equipped with thermo-couples for monitoring the fuel temperature during the reactor operation, a schematic drawing of the fuel element is shown in Figure 1.

2.1.3 Control rods

The reactivity control of the reactor is handled by four absorbing rods:

- Pulsation rod (P rod): localized in ring C and composed of a core borated graphite cladding,
- Safety rod (S rod): localized in ring C
- Regulating rod named R rod: localized in ring D, S, C, and consists of two overlapping parts: the absorbent part (poison) of boron carbide powder (B_4C) followed by a part of fuel (follower) similar to that of the combustible elements.

2.1.4 Irradiation facilities

There are two irradiation facilities located inside the reactor core: the pneumatic irradiation system (named rabbit channel), localized in the ring F, and the central thimble of aluminum pipe located at the center of the fuel rings and the Lazy Susan facility is a rotary specimen rack with 40 positions which allows the irradiation of 80 samples at the same time. It is placed in a circular well within the radial reflector and the rotation mechanism to allow a homogeneous neutron flux exposure of all the samples. There are four horizontal beam channel ports penetrating the concrete shielding and extending inside the pool towards the reflector. In addition, there is the thermal column consisting of a cavity in which it is possible to insert graphite blocks with different thicknesses to obtain different thermal neutron spectra.

Fig. (2): Ion-exchange and activated carbon filter [picture took by Beya]

2.2 Cooling circuit

The reactor core is cooled by the circulation of ordinary water, which is also considered as a moderator as well as a biological shield. The cooling principle is carried out as primary circuit circulates the water from the reactor pool through its piping and a heat exchanger.

The pool cooling system can be divided into four distinct parts, as shown in Figures (2-5):

1. The reactor pool
2. The Purification circuit, Figs.(2 &3)
3. Primary circuit, Fig.(4)
4. Secondary circuit, Fig.(5)

Fig. (3): Geiger-Muller and pump of purification circuit. [picture took by Beya]

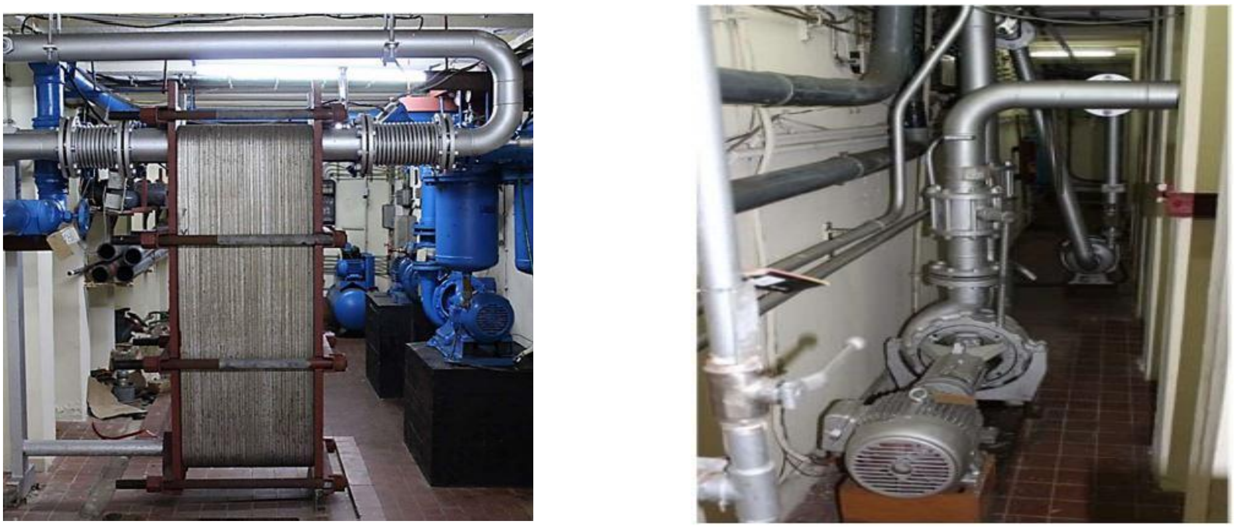

Fig. (4): Heat exchange (left) and Pumps (right) of the primary circuit. [picture took by H. Beya]

Fig. (5): Pumps and filters (left) [picture took by H. Beya] and cooling towers (right) [picture took by S. Ilunga] of the secondary circuit

2.3 Spent fuel storage

Inside TRICO-II reactor building, there are two temporary storage places for spent fuel and damaged fuel rod. The first one is the spent fuel storage wells shown in Fig. 6, which is capable of receiving 76 spent fuel elements and it is filled with demineralized water. A regular follow-up of the conductivity of this water is carried out to preserve the integrity of the fuel clad. The second one is the storage racks located inside the reactor tank shown in Fig.7. TRICO-II was in extended shutdown state since November 19th, 2004. From 22 October to 19 November 2008, as part of the IAEA's TRICO-II fuel element verification mission, certain fuel elements were transferred from the core to the storage racks of the TRICO-II reactor vessel.

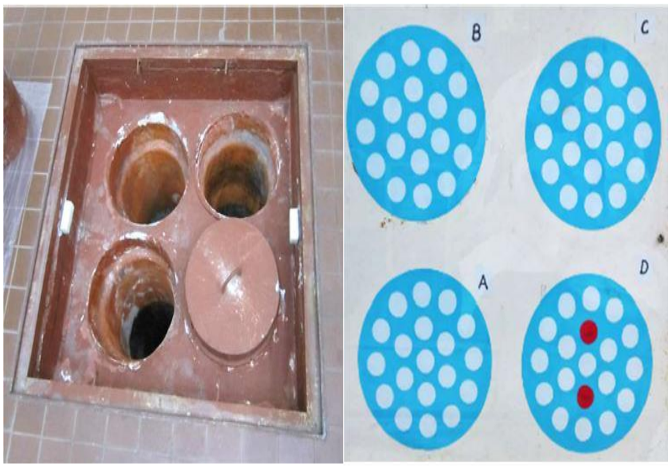

Fig. (6): Spent fuel storage wells with actual configuration

Fig. (7): TRICO-II reactor tank [taken by Beya]

The reactor facility has 4 floors: the underground floor, the ground floor, the first floor and the second floor. In addition to these floors, there are two virtual floors, representing the floor of the spent fuel storage and the storage tank for liquid waste, are added to make more practical the collection of the reactor inventory of equipment. The main equipment inventory items of TRIGA-II reactor is described in the IAEA-TECDOC-1832 annex [13]. Those items are mentioned in section 5.1.a and are used in the calculation of the cost estimate to get an overestimate cost values.

3. Modeling of TRICO-II Reactor

3.1 Reactor core modeling

TRICO-II core was modeled using MCNPX-code [18]. The fuel rod was modeled through Zr rod, Mo-disk, the stainless-steel cladding, and a void gap of about 0.035 cm between the fuel meat and the cladding; also, the control rods, aluminum grid plates, graphite element, ring positions, reflector, reactor tank and concrete shielding were modeled as shown in Figures (8-10).

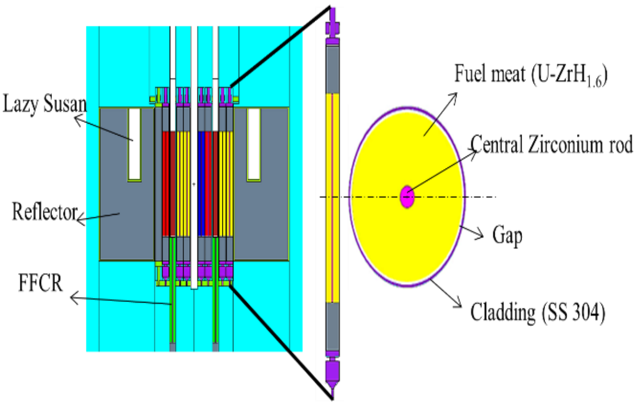

Fig. (8): MCNP vertical model of core and FE

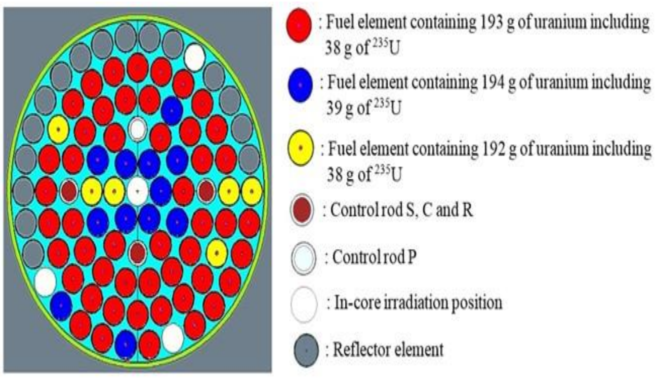

Fig. (9): Horizontal view of MCNP model

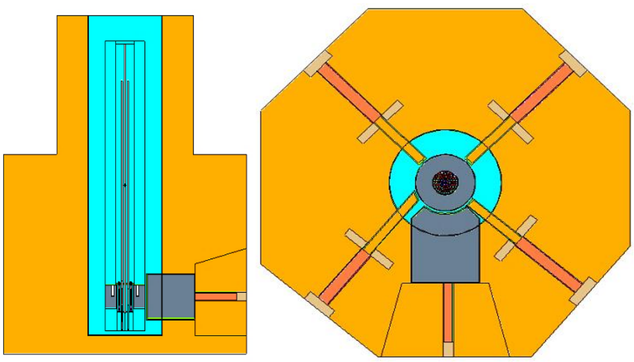

Fig. (10): MCNP model of vertical cross-sectional (left) and horizontal view (right)

3.2 Spent fuel modeling and characterization

The Monte Carlo MCNPX code [17] was used to model and calculate the spent nuclear fuel inventories (actinides and non-actinides) with its radioactivity at its maximum discharge burn-up as shown in Table 1.

It is important to note that, the first core configuration contain 2.576 kg of U-235, while each of the second and the third core configuration contain 2.653 kg of U-235, with 77.0 g of U-235 more than the first configuration. During the second and third configurations, TRICO-II was operated at an average power of 250 kW_{th} for 20.5 and 112.6 effective full power days, respectively.

Table (1): Important radio-nuclide and activity of spent fuel for the 3rd core of TRICO-II

Nuclide	Activity (Bq)	Mass (g)
	Actinides	
U-234	2.85E+05	1.24E-03
U-235	2.09E+08	2.61E+03
U-236	1.67E+07	6.98E+00
U-238	1.34E+08	1.08E+04
Np-237	2.65E+05	1.02E-02
Pu-238	1.47E+07	2.31E-05
Pu-239	8.81E+09	3.84E+00
Pu-240	1.94E+08	2.31E-02
Pu-241	2.24E+08	5.86E-05
Pu-242	9.44E+01	6.44E-07
Am-241	2.53E+07	2.00E-04
	Non-actinides	
Kr-85	5.22E+10	3.58E-03
Sr-90	1.51E+12	2.88E-01
Y-90	1.51E+12	7.50E-05
Cs-137	1.85E+12	5.76E-01
Sm-151	6.81E+13	6.98E+01

From Table (1), it could be noticed that the total activity for the spent fuel is equal to 7.30E+13Bq and the activity of each fuel element is 1.04E+12Bq. These values are necessary for radiation protection management during the handling, transport, and final storage of the spent fuel.

Also, the produced fissile nuclides (Pu-239 and Pu-241) during TRICO-II operation and their mass accumulation was about 4.0 g.

4. Decommissioning plan of TRICO-II research reactor

4.1 Decommissioning strategy

The immediate dismantling is the most adopted decommissioning option with the purpose of using the TRICO-II buildings as a museum or a tourist place telling the story of nuclear science. In DRC, the regulatory body was created for the control and regulation of activities related to the protection of people and environment from the harmful effects of ionizing radiation and the physical protection of nuclear materials and nuclear facilities [11].

4.2 Organization and responsibilities of the decommissioning plan

An organization chart was planned for the implementation of the decommissioning activities as shown in Figure 11.

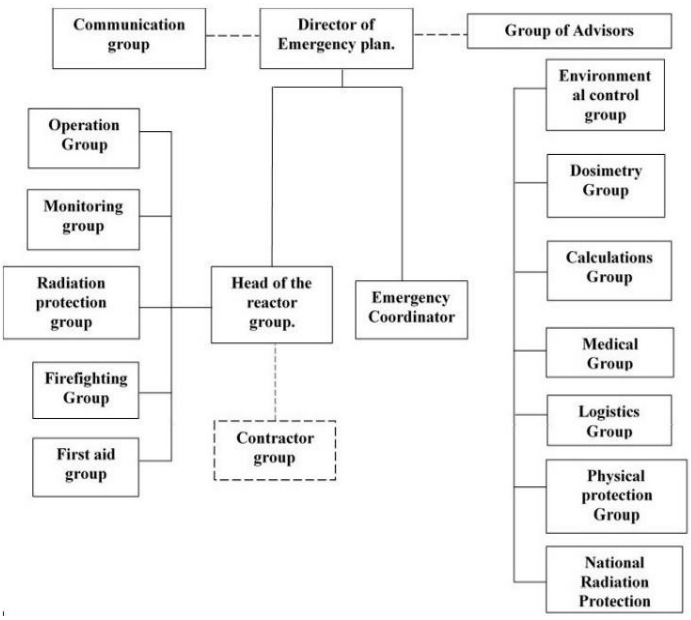

Fig. (11): Organizational chart of the stakeholders during the Decommissioning activities

4.3 Decommissioning Activities

The decommissioning activities of TRICO-II are:

4.3.1 Pre-decommissioning actions

- Surveys, characterization, calculations, and safety assessments of the contaminated equipment,
- Preparing management group,
- Spent fuel characterization,
- Removal of spent fuel from the reactor to the spent fuel storage
- Drainage/drying of the primary cooling system and decontamination
- Removal of operational waste.

4.3.2 Decontamination and dismantling in the controlled area

- Procurement and tools for dismantling
- Dismantling of reactor internals
- Drainage of pool water
- Dismantling of upper cover of the biological shielding and reactor vessel
- Dismantling of lower part of the biological shield
- Dismantling of lower part of the vessel, horizontal channels, and thermal columns
- Dismantling of primary components
- Dismantling of auxiliary components
- Removal of contaminated soil
- Decontamination of building surfaces
- Final survey/release of the reactor building

4.3.3 Site remediation

- Preparation of tools and procurement, for dismantling out of the controlled area
- Dismantling the primary cooling loop and the cooling tower
- Demolition of cooling tower and connected buildings
- Final site survey

4.3.4 Radioactive waste management

- Preparation of radioactive waste management
- Management of historical/legacy waste
- Management of decommissioning waste

4.3.5 Spent fuel management

- Preparation/licensing of long-term spent fuel storage
- Operation of the long-term spent fuel storage during decommissioning

4.3.6 Project management and site support

- Site infrastructure and support
- Project management, manpower and support

4.3.7 Research and development (R&D)

- R&D for spent fuel and structural material characterization
- R&D for dismantling

5. Cost estimation for decommissioning

5.1 Methodology

Decommissioning cost involves a number of discrete sequential activities [9, 12,13] as follows: -

5.1.1 Database for the inventory

Structures and systems inventories which need characterization and measurements of the radiological parameters such as contaminated surfaces (inner and outer), activated constructions and equipment are shown in Table 2.

Table (2): Main inventory items for TRIGA-II reactor

List of main inventory items	Expected quantities
Demineralizer Resin [ton]	0.1 ± 10%
Tanks [ton]	1.6 – 3.8
Piping and valves [ton]	2.6 – 15
Heat exchanger [ton]	2.2 ± 10%
Structural equipment (stairs, core bridge, covers) [ton]	2.1 – 6
Neutron Beam Tubes and Port [ton]	1.4 – 3.5
Ventilation (duct, fan, motor, stack, filter) [ton]	10 – 20
Core Assemblies (Control rods, Grid Plate) [ton]	0.6 – 0.9
Rotating Specimen Rack (RSR) [ton]	0.5 -0.8
Graphite elements and graphite reflectors [ton]	2.4 – 6.8
Cables and Cable Trays [ton]	2 – 4
Liquid water and sludge [m^3]	25 ± 10%
Pool liner, Reactor liner [ton]	12 – 15
Decontamination Building Surface [m^2]	1500 – 3000
Monitoring Building Surface [m^2]	1500 – 3000
Masonry [ton]	39.1 – 106
Bio-shielding concrete [ton]	359 – 494

5.1.2 Unit factors database

This database is for workforces, production of secondary waste, consumable, composition of working groups and associated parameters for each task (e.g., cost factors for labor unit and measured exposure values).

5.1.3 Decommissioning options

The selected decommissioning strategy is the main issue for selecting the decommissioning option. The associated cost calculation should cover all relevant possibilities being considered in the selected option.

5.1.4 Cost of the selected options

Different cost estimates are derived for decommissioning projects, based on:-

- Order of magnitude estimate: without detailed engineering data, where an estimate is prepared using scale-up and approximate ratios.
- Budgetary estimate: based on the use of flow sheets, layouts, and equipment details, where the scope has been defined, but the detailed engineering has not been performed.
- Definitive estimate: where the details of the project have been prepared and its scope and depth are well defined.

For TRICO-II research reactor, we will use in some items the first estimate (Order of magnitude) and for other items the budgetary estimate; knowing that we don’t have enough engineering data to apply the definitive estimate. However, this aspect (engineering data) has to be considering in the future.

5.2 Management of decommissioning budget

Adequate budgets need to be preserved and secured to cover the costs of decommissioning and management of spent fuel and radioactive waste. For nuclear reactors, spent fuel management costs should be considered unless they are a part of the operational costs. Moreover, these cost estimates should take into consideration the analysis of associated risks and uncertainties during decommissioning. Regulatory frameworks are required and have been taken into consideration for the creation of decommissioning budget. It is required to ensure that;

- Contributions to the budget are made by facilities using radioactive material during their operation so that sufficient funds are available at the time of final shutdown in order to cover necessary decommissioning and waste management expenses,

- Contributions are comparable with the estimated service life of the reactor,
- Periodic review and assessment of the funds.

5.3 Cost Estimation using the IAEA Cost Estimation for Research Reactors in Excel (CERREX-D) code

5.3.1 Description of CERREX-D code

The software code, CERREX-D is based on the ISDC (International Structure for Decommissioning Costing) described in [4] and is implemented in Microsoft Excel. The code consists of a set of representative decommissioning and waste management items and associated amounts. The unit factors incorporate all relevant preparatory and activities associated with each activity. The main input parameters for implementing the ISDC methodology in the CERREX code:

- Inventory and waste-related information
- Implementation of unit factor information for the inventory-dependent and waste management activities,
- Identification of the cost elements, including inventory or waste management activities,

The ISDC defines eleven principal items which constitute the main input of CERREX code are:

1) Preparatory works
2) Items of facility shutdown
3) Works for safe enclosure and entombment
4) Works of dismantling in the controlled area
5) Management of radioactive waste
6) Infrastructure of the site
7) Dismantling, demolition, and site restoration
8) Management of the work
9) Research and development
10) Nuclear fuel and nuclear material
11) Expenditures and miscellaneous

In the ISDC cost calculation structure, each elementary calculation item involves [3]:

- Input fields for activation/deactivation
- ISDC definition
- Input data segments for unit factors
- Workforce / cost calculation segment
- Input data segment for period dependent activities and for collateral cost
- Inventory data segment
- Waste input data segment

Segments for unit factors have been defined in order to enable the use of values for individual unit factors by the users. Cells in the CERREX software containing formulas have been locked in order for the user not to overwrite the formulas unintentionally when entering data in the wrong place [3].

5.3.2 Input data and assumptions

The time period of the decommissioning works was determined according to the schedule of the activities. The secondary waste production unit factors were defined according to the annex of the IAEA-TECDOC-1832 [13]. Based on the actual socio-economic situation of DRC, labor cost unit factors proposed and considering the quality and quantity of each particular decommissioning activity are show in Table (3).

Table (3): Labor cost unit factors

	Labor cost unit factors & overheads				[USD/h]			
	LBR	**SKW**	**TCN**	**ADM**	**ENG**	**SEN**	**MNG**	**AVW**
Licensee	1.1	1.3	2.8	3.2	3.4	4.2	6.0	2.4
Contractor	1.4	1.7	3.6	4.2	4.4	5.5	7.8	3.1

Where; Labor (LBR), Skilled worker (SKW), Technician (TCN), Administrator (ADM), Engineer (ENG), Senior engineer (SEN), Manager (MNG) and Averaged worker (AVW).

6. RESULTS OF COST ESTIMATE

The results of the cost estimate of the decommissioning of TRICO-II and estimation of waste quantities using the CERREX code are shown in Tables 4 and 5.

Based on the data compiled by The IAEA related to the decommissioning cost of selected research reactors versus thermal power, the cost of decommissioning of TRIGA reactors with power levels of 1MW$_{th}$ or more can range from US$ 1-10 million (2013 price levels). So, It can be noticed from these tables that the estimated value for the decommissioning cost of TRICO-II research reactor is about US$ 5,918,301, which is in the range of IAEA estimates [13, 14]. Also, the total amount of the radioactive waste generated from the decommissioning of TRICO-II is about 800 tons of low-level waste.

Table (4): Summary of the cost estimates of ISDC Items for TRICO-II

© CERREX-D_Cost Estimation for Research Reactors in Excel; IAEA project DACCORD			ISDC Level 2 data of the costing case				Currency	USD
Case:		TRICO II_DRC Research Reactor	Retrieval of calculated data into ISDC Level 2 format					
Reactor:		Triga-Mark II; 100 kW-1 MW	Total calculated data		Calculated ISDC cost categories			
Operation:		Limited Operation	Workforce	Costs	Labour costs	Investment	Expences	Contingency
Version: AM		© International Atomic Energy Agency	[man.h]	[USD]	[USD]	[USD]	[USD]	[USD]
A	ISDC No.	ISDC Name	196,048	5,918,301	616,006	291,825	4,039,593	970,876
	01	Pre-decommissioning actions	119,065	624,162	439,702	6,000	89,940	88,519
	01.0100	Decommissioning planning	83,965	428,546	310,525	0	62,105	55,917
1	01.0200	Facility characterisation	25,380	140,883	92,835	6,000	18,567	23,480
1	01.0300	Safety-, security- and environmental studies	8,100	42,811	29,730	0	5,946	7,135
	01.0500	Authorisation	1,620	11,922	6,612	0	3,322	1,987
	02	Facility shutdown activities	8,460	27,474	19,079	0	3,816	4,579
	02.0100	Plant shutdown and inspection	2,160	9,033	6,273	0	1,255	1,505
1	02.0200	Drainage and drying of systems	2,700	7,904	5,489	0	1,098	1,317
1	02.0500	Removal of system fluids, operational waste and redundant ...	3,600	10,538	7,318	0	1,464	1,756
1	03	Additional activities for safe enclosure or entombment	0	360,000	0	0	300,000	60,000
	04	Dismantling activities within the controlled area	46,863	382,373	104,806	177,998	35,841	63,729
1	04.0100	Procurement of equipment for decontamination and ...	2,700	190,726	7,449	150,000	1,490	31,788
	04.0400	Removal of materials requiring specific procedures	225	784	545	0	109	131
	04.0500	Dismantling of main process systems, structures and components	25,276	115,395	62,628	10,259	23,276	19,233
	04.0600	Dismantling of other systems and components	5,712	18,030	11,798	239	2,989	3,005
	04.0700	Removal contamination from building structures	12,950	57,438	22,387	17,500	7,977	9,573
	05	Waste processing, storage and disposal	21,661	1,554,292	52,419	107,828	1,134,996	259,049
1	05.0100	Waste management system	9,178	650,509	22,211	45,614	474,266	108,418
1	05.0800	Management of decommissioning intermediate level waste	1,320	131,320	3,194	6,600	99,639	21,887
1	05.0900	Management of decommissioning low level waste	6,258	434,836	15,144	31,290	315,929	72,473
1	05.1000	Management of decommissioning very low level waste	732	50,894	1,773	3,662	36,977	8,482
1	05.1100	Management of decommissioning very short lived waste	50	294	121	50	74	49
1	05.1200	Management of decommissioning exempt waste and mat...	4,122	286,439	9,976	20,612	208,111	47,740
1	06	Site infrastructure and operation	0	480,000	0	0	400,000	80,000
1	07	Conventional dismantling and demolition and site restoration	0	54,000	0	0	45,000	9,000
1	08	Project management, engineering and support	0	1,200,000	0	0	1,000,000	200,000
1	09	Research and development	0	216,000	0	0	180,000	36,000
1	10	Fuel and nuclear material	0	300,000	0	0	250,000	50,000
1	11	Miscellaneous expenditures	0	720,000	0	0	600,000	120,000

Table (5): Estimation of the waste quantities

Summary of waste quantities in the costing case			
ILW	Intermediate Level Waste (decommissioning and hist./legacy)	9.9	[t]
LLW	Low Level Waste (decommissioning and hist./legacy)	128.3	[t]
VLLW	Very Low-Level Waste (decommissioning and hist./legacy)	146.0	[t]
EW	Exempt Waste (decommissioning and hist./legacy)	522.2	[t]
NRW	Non-radioactive Waste (all types)	11.0	[t]
	Total radioactive waste	806.5	[t]

. CONCLUSIONS

- TRICO-II research reactor was modeled using MCNPX to calculate the radio-nuclides inventory and its activities for the spent nuclear fuel. The results showed that the total activity for the spent fuel is equal to 7.30E+13Bq and the activity of each fuel element is 1.04E+12Bq. Also, the produced fissile nuclides (Pu-239 and Pu-241) during TRICO-II operation and their mass accumulation was about 4.0 g. The results are essential for spent fuel characterization and to support the radiation protection requirements and environmental safety limits during the handling and choice of the suitable transport cask for the spent fuel for decommissioning purposes of the reactor.

- A preliminary decommissioning plan for TRICO-II has been established based on the immediate dismantling strategy and the organization chart of the decommissioning activities and the input inventory items have been defined.

- The cost estimate of the decommissioning of TRICO-II was performed using the IAEA CERREX-D software, which is based on the international structure for decommissioning costing (ISDC). The estimated cost was about US$ 6 million, which was in the acceptable range of other TRIGA-II reactors around the world (US $1-10). The results showed that the total amount of radioactive waste generated from the decommissioning of TRICO-II is about 800.0 tons of low-level radioactive waste.

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REFERENCES

[1] M. Shaat and Rowayda F. Mahmoud, A Preliminary Decommissioning Plan for a Research Reactor, International Atomic Energy Agency (IAEA) Conference on Research Reactors: Addressing Challenges and Opportunities to Ensure Effectiveness and sustainability, Buenos Aires, Argentina, 25- 29 Nov. 2019

[2] IAEA, Power Reactor Information System, www.iaea.org/pris, IAEA, 2016

[3] The Practice of Cost Estimation for Decommissioning of Nuclear Facilities, OECD, Paris, NEA, 2015

[4] International Atomic Energy Agency, Decommissioning of Nuclear Power Plants, Research Reactors and Other Nuclear Fuel Cycle Facilities, IAEA Safety Standards, Specific safety Guide No SSG-47, IAEA, Vienna, 2018

[5] Michele Laraia, Nuclear Decommissioning: Planning, execution and international experience, Wood head Publishing Series in Energy N°36, Oxford Cambridge Philadelphia New Delhi, Wood head Publishing Limited, 2012

[6] International Atomic Energy Agency, Decommissioning of Nuclear Power Plants and Research Reactors, IAEA Safety Standards Series, Safety Guide, No.WS-G-2.1, IAEA, Vienna, 1999

[7] International Atomic Energy Agency, Decommissioning of Facility, IAEA Safety Standards, No. GSR Part 6, IAEA, Vienna, 2014

[8] Sed, L.J., Reisenweaver, D., International Decommissioning Strategies, Proceedings of the International Conference on Research Reactor Utilization, Safety, Decommissioning, Fuel and Waste Management, Chile, 2005

[9] Heritier Beya T., Safety Assessment and Cost Estimates for the Decommissioning of D.R. Congo Research Reactor (TRICO II), A thesis submitted in partial fulfillment of the requirements for the degree of Master of science in Nuclear Science & Technology, Department of Nuclear & Radiation Engineering, Faculty of Engineering, Alexandria University, Egypt, 2019

[10] Taboas A., Moghissi A. A., Laguardia T.S., American Society of Mechanical Engineers. Environmental Engineering Division, et al., "The Decommissioning Handbook", ASME, New York, N.Y., 2004

[11] ThierfeldtS.; PodlahaJ.; hansP.; holliM., Inventory of best practices in the decommissioning of nuclear installations, Final report for contract

TREN/04/NUCL/ S07.40035 of the European Commission, Brenk System planning, Gmbh, 2007

[12] International Atomic Energy Agency. Standard Format and Content for Safety Related Decommissioning Documents, Safety Report Series No. 45, IAEA, Vienna, 2005

[13] International Atomic Energy Agency, "Data Analysis and Collection for Costing of Research Reactor Decommissioning", IAEA TECDOC Series, IAEA-Tecdoc-1832, IAEA, Vienna, 2017

[14] International Atomic Energy Agency, Research Reactor Decommissioning Databank, https://www.iaea.org/OurWork/ST/NE/NEFW/WTS-Networks/IDN/researchreactors.html

[15] International Atomic Energy Agency, "Classification of Radioactive Waste", Safety Standards Series No. GSG-1, IAEA, Vienna, 2009

[16] J. G. Marques and A. Kling, Radioactive waste from Research Reactor Operation and Decommissioning, InstitutoTecnológico de Nuclear, Centro de Física Nuclear da Universidade de Lisboa, Portugal, January 2012

[17] Antti RÄTY, Petri KOTILUOTO, "FIR1 TRIGA Activity Inventories for Decommissioning Planning", VTT Technical Research Centre of Finland Ltd, 2016

[18] MCNPX 2.7 User's Manual Code, license number #150863.