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Comissioning of the IEA-R1 Nuclear Reactor New Heat Exchanger

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Abstract: This work presents results on the commissioning of the new heat exchanger of the IEA-R1 nuclear reactor in the occasion of its operational power upgrade from 2 MW to 5 MW, in comparison to the values calculated in the project of IESA Design and Equipments Company. This reactor is a swimming pool type, light water moderated and with graphite reflectors, used for research purposes and medical radioisotopes production. During monitoring procedures, issues were observed on the reactor operation at 5 MW mainly due to the ageing of the reactor's oldest heat exchanger (TC-A) and excessive vibrations at high flow rates on the other installed heat exchanger (TC-B). So it was decided to provide a new IESA heat exchanger with 5 MW capacity to definitely substitute the TC-A heat exchanger. The results show that the IEA-R1 nuclear reactor can be operated safely and continuously at 5 MW with the new IESA heat exchanger.

Key words: Heat exchangers, IEA-R1 nuclear reactor, research nuclear reactors, radioisotope production.

1. Introduction

The IEA-R1 nuclear reactor is suitable for use in basic and applied research as well as in production of medical radioisotopes. Installed at Nuclear and Energy Research Institute (IPEN-CNEN/SP), in Sao Paulo, it is one of the four research reactors operating in Brazil [1]. The reactor is a swimming pool type, light water moderated and build with graphite reflectors. It was started up in 1957, being the first criticality for the south hemisphere. The reactor was originally designed to operate at 5 MW, although until the year of 2001 it was used at 2 MW.

Due to a recent increase on the demand of radioisotopes for medical diagnoses and therapies applications in Brazil [2], it was decided to upgrade IEA-R1 power to 5 MW in continuous operation regime. This decision triggered a handful of recent studies and preparation for IEA-R1 [3-5].

Thus, according to IAEA procedures, ageing management studies for the reactor were conducted resulting in critical components identification. Also they were made recommendations on the implementation for test scheduling and standardization procedures to organize operational data and documents. One of the main results of these procedures was the need of monitoring actions of the two heat exchangers, the two primary circuit pumps and the data acquisition system.

The reactor cooling system is constituted by two independent heat exchangers flow circuits. In the primary flow circuit the cooling fluid has two alternatives of flow: inside the tubes of heat exchanger A (TC-A) or inside the shell of heat exchanger B (TC-B). Then, the cooling fluid flux is directed to a

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flowmeter and then returns to the bottom of the pool through a diffuser to achieve a better mixture with the pool water. Motor driven isolation valves are installed in the inlet and outlet streams. The circuit schematic diagram is presented in Fig. 1.

The secondary cooling circuit has two cooling towers, two heat exchangers, two pumps and valves, as presented in Fig. 2. The reactor oldest heat exchanger (TC-A) was design and build by Babcock & Wilcox in 1957.

In 1974, a newer heat exchanger (TC-B) was designed and build by CBC (Brazilian Pressure Vessels Company), being installed together with the second cooling system. Both were designed to a 5 MW reactor power operation, but until last decade, there was no need to operate at power higher than 2 MW. In recent years although, the substantial increase on the demand for medical and therapy diagnoses radioisotopes in Brazil leaded to studies for increase its power operation to 5 MW and operate at continuous regime.

To fulfill this demand, IPEN-CNEN/SP decided to upgrade the IEA-R1 power to 5 MW. Studies on the ageing management for the IEA-R1 reactor were conducted according to IAEA procedures described in the technical report 338 [6] and technical document 792 [7]. As result of these studies critical components within the ageing management program were identified.

Also recommendations were made on the implementation of test scheduling and standardization procedures to organize data and documents. One of the main results was the need of monitoring the two heat exchangers, the two primary circuit pumps and the data acquisition system.

During monitoring procedures, issues were observed on the IEA-R1 operation at 5 MW mainly due to the ageing of TC-A heat exchanger and vibration problems at high flow rates on TC-B heat exchanger. Therefore, it was decided to work with 3.5 MW and provide a new IESA heat exchanger with 5 MW power capacity, to substitute the TC-A heat exchanger.

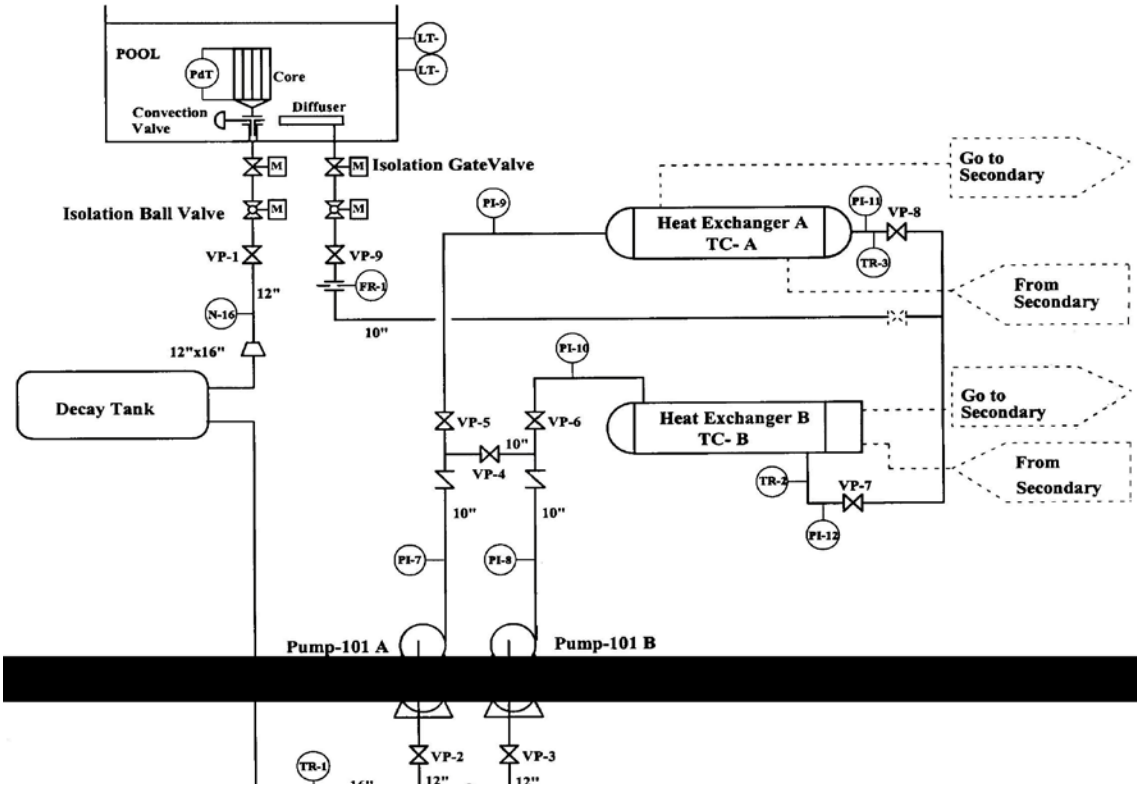

Fig. 1 IEA-R1 reactor primary cooling circuit.

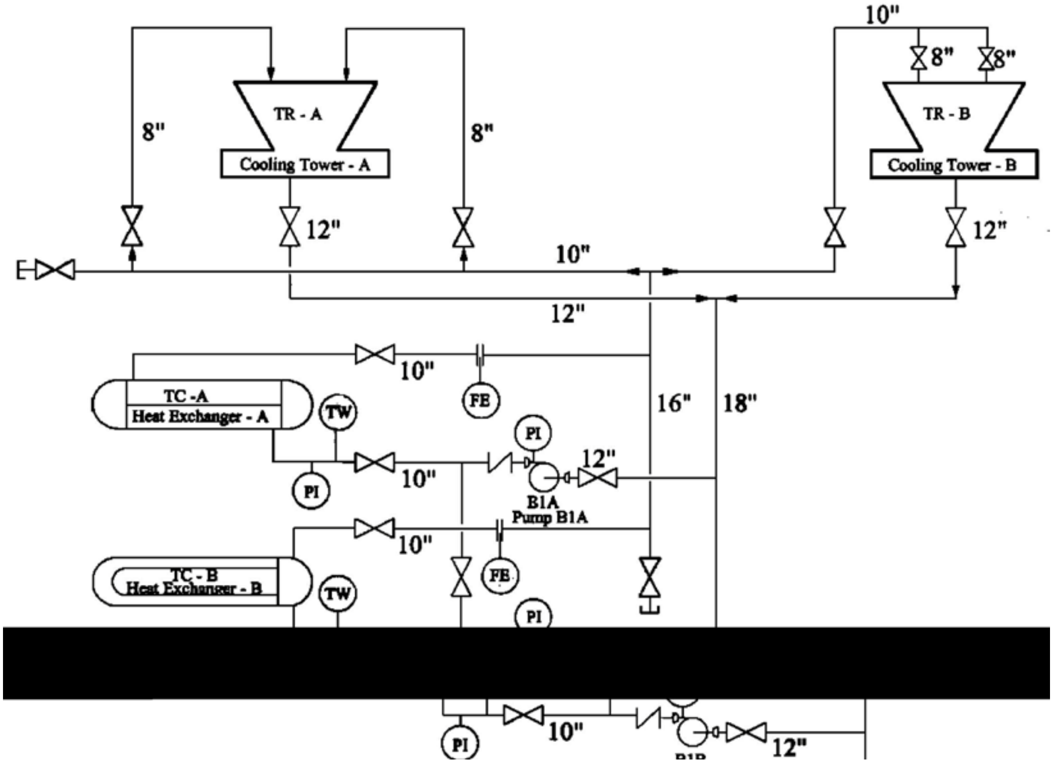

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Fig. 2 IEA-R1 reactor secondary cooling circuit.

2. Materials and Methods

The studied procedures for commissioning were executed in two sets of experiments: initial essays with the reactor powered off; and essays with the reactor powered on with operational conditions of 3.5 MW, 4.0 MW and 5.0 MW.

The B cooling tower was used in all experiments, and the target objectives of experiments were:

- to obtain pressure loss in IESA heat exchanger at reactor operational flow conditions in the primary cooling circuit, shell side;
- to obtain pressure loss in IESA heat exchanger at reactor operational flow conditions in the secondary cooling circuit, tube side;
- to obtain IESA heat exchanger vibrations at reactor operational flow conditions;
- to obtain the flow coast down at 5.0 MW and 3,500 gpm.

Two Fischer® pressure transmitters for pressure loss measurement were used in the experiments. A Bruel & Kjaer® accelerometer was used for vibration measurement, including pump vibration measurements. For pressure measurement two bourdon manometers were used. All measurement devices were installed in the IESA heat exchanger, as shown in Fig. 3.

The primary flow rate was tested ranging from 2,700 gpm to 3,830 gpm. Tests with the secondary flow rate ranged from 1,900 gpm to 2,300 gpm.

In Fig. 4, the digital data acquisition system used to acquire the values of primary and secondary flow rates and temperatures is shown. The signals of pressure transmitters and accelerometer were acquired with this portable acquisition system, built with LabVIEW® software and DAQ-Hardware, both from National Instruments®.

Calculations were made with the thermocouple measured values, in order to evaluate the energy balance in both ends of IESA heat exchanger.

The percentual errors of these calculations were obtained from Eq. (1).

$$\varepsilon = (N - M)/N \tag{1}$$

where:

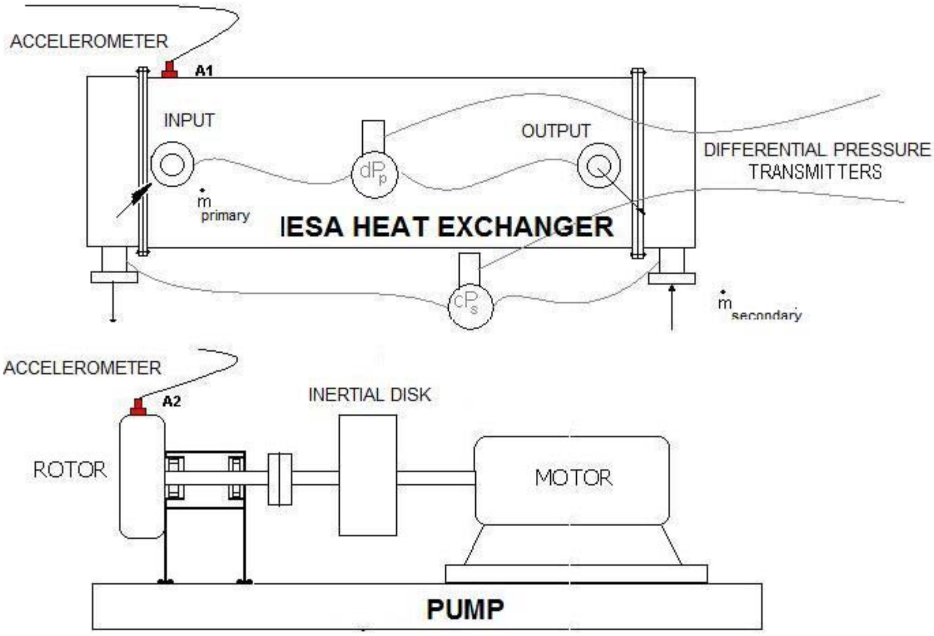

Fig. 3 Heat exchanger and pump instrumentation.

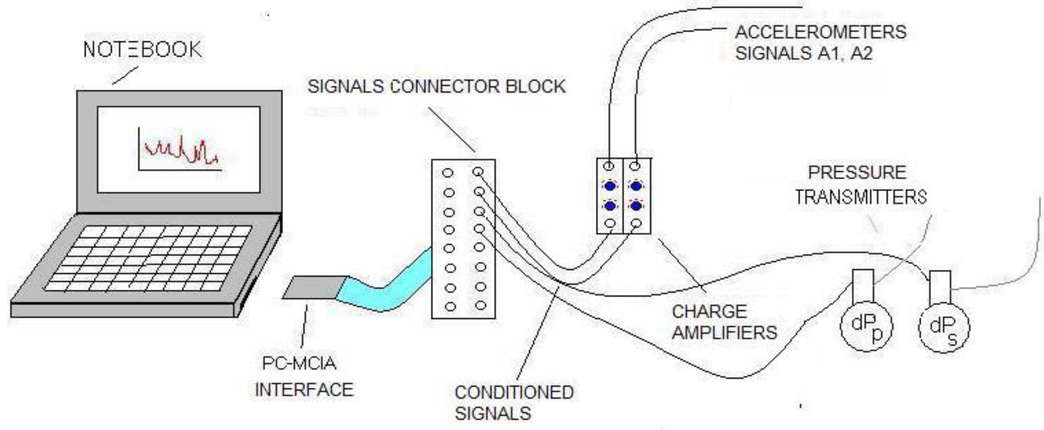

Fig. 4 Portable data acquisition digital system.

N = nominal reactor power;
M = measurement of heat exchanged.

3. Results and Discussion

The operational conditions for all experiments are presented in Table 1.

Table 2 presents the energy balance results for the IESA heat exchanger. For the energy balance of the primary side (tube side) of heat exchanger, a 3% error can be observed for the 5 MW operational condition, which is acceptable. For the 3.5 MW operational condition the energy balance error was larger, 6%, but it was also acceptable, because for smaller temperature differences small errors in temperature measurements produce larger errors in the energy balance. Similar results were obtained for other reactors and showed no issues [8]. The thermocouples were calibrated and well installed in the heat exchanger, therefore this error probably is generated by heat loss in the pipeline and decay tank.

To analyze the pressure losses and the vibrations for the IESA heat exchanger the software Matlab® was used. Statistical values data as rms, maximum and minimum peak, standard deviation, skewness, kurtosis

Table 1 Operational conditions for the experiments.

Power (MW)	*Qp* (gpm)	*Qs* (gpm)	*Tpe* (°C)	*Tps* (°C)	*Tse* (°C)	*Tss* (°C)	*Tte* (°C)	*Tts* (°C)
0	2,700	1,910	22.35	18.70	16.49	18.06	18.45	16.49
0	2,900	1,915	22.40	18.70	16.88	18.15	18.35	16.79
0	3,000	2,000	22.40	18.70	17.2	18.20	18.35	17.08
0	3,100	2,000	22.45	18.70	17.28	18.15	18.45	17.18
0	3,300	2,100	22.45	18.74	17.37	18.15	18.54	17.28
0	3,500	2,200	22.45	18.84	17.47	18.25	18.54	17.37
0	3,700	2,300	22.55	18.93	17.47	18.25	18.64	17.37
0	3,830	2,430	22.55	18.93	17.57	18.25	18.64	17.57
0	3,500	2,200	22.55	19.03	18.06	18.35	18.64	17.67
3.5	3,200	2,000	32.50	28.60	24.80	29.40	29.80	24.60
4.0	3,500	2,200	33.90	29.70	25.00	30.10	30.60	24.80
5.0	3,600	2,300	36.00	30.90	25.70	31.50	32.10	25.30

Qp = primary flow; *Qs* = secondary flow; *Tpe* = inlet primary heat exchanger temperature; *Tps* = outlet primary heat exchanger temperature; *Tse* = inlet secondary heat exchanger temperature; *Tss* = outlet secondary heat exchanger temperature; *Tte* = inlet cooling tower temperature; *Tts* = outlet cooling tower temperature.

Table 2 Energy balance for the IESA heat exchanger.

Nominal Power reactor (kW)	Primary flowrate (gpm)	Primary mass flow (kg/s)	ΔTP (°C)	Primary heat exchanged (kW)	Error (%)
3,500	3,200	201.6	3.9	3292	6.0
4,000	3,500	220.5	4.2	3878	3.0
5,000	3,600	226.8	5.1	4843	3.0

and power spectral densities for the accelerations in the shell and differential pressures primary/secondary side were calculated for the different experimental conditions.

Tables 3-5 presents the results obtained with Matlab® software, regarding the pressure losses in the primary circuit (shell side), pressure losses in the secondary side (tube side) and the shell accelerations of the IESA heat exchanger for different operational reactor flow rates and power. To the first eight experimental conditions presented in Tables 3 and 4, the accelerometer signals were conditioned with a 3,000 Hz low-pass filter and 0.2 Hz high–pass filter. The accelerometer and pressure transmitter signals were digitalized with a 5,000 Hz scanning frequency during 20 s. In the 9th experimental condition presented in Tables 3 and 4, flow coast down experiment, the signals were digitalized with a 1,000 Hz scanning frequency during 180s. In reactor powered experiments, for the 10th, 11th and 12th conditions presented in Tables 3 and 4, the signals were digitalized with a scanning frequency 4,000 Hz during 30 s.

To the project conditions for the IESA heat exchanger, primary flow rate Q_P = 3,600 gpm and secondary flow rate Q_S = 2,300 gpm with 5.0 MW heat transfer capacity, we can observe that the result to the primary side (shell side), ΔP_{Prms} = 0.5126 bar was little higher as the value calculated by IESA ($\Delta P_{Pallowed}$ = 0.45 kgf/cm^2 and Δ $P_{Pcalculated}$ = 0.408 kgf/cm^2). In the secondary side (tube side), the value measured wasΔ P_{Srms} = 0.0753 bar, similar as the value calculated by IESAΔ($P_{Sallowed}$ = 0.20 kgf/cm^2 and $\Delta P_{Scalculated}$ = 0.0714 kgf/cm^2). These values from IESA were obtained from Ref. [9].

The difference between the values calculated by IESA and the measured values at the comissioning in the primary side can be explained due the complex geometry from the bundle of tubes, and the direction changes in the flow in the shell side, cross-flow and stagnation regions among other effects.

Table 3 Results for the primary pressure losses (shell side)—IESA heat exchanger.

Power (MW)	Flow (gpm)	ΔPP_{rms} (bar)	σ *Psp* (bar)	ΔPP_{max} (bar)	ΔPP_{min} (bar)	Skewness	Kurtosis
--------	2,700	0.2825	0.0109	0.3144	0.2506	0.1142	2.6907
--------	2,900	0.3330	0.0324	0.4301	0.2272	0.0096	2.8775
--------	3,000	0.3531	0.0317	0.4542	0.2375	0.0298	3.7030
--------	3,100	0.3721	0.0270	0.4623	0.2964	0.0928	3.3236
--------	3,300	0.4240	0.0320	0.5344	0.3323	0.0553	3.1057
--------	3,500	0.4736	0.0293	0.5579	0.3902	0.0167	2.9001
--------	3,700	0.5324	0.0255	0.5996	0.4553	0.0022	3.0390
--------	3,830	0.5584	0.0222	0.6308	0.4982	0.0719	2.8104
--------	3,500	-----	-----	----	----	----	----
3.5	3,200	0.4160	0.0443	0.4659	0.2486	0.3983	2.0647
4.0	3,500	0.4850	0.0430	0.4985	0.4407	-0.4261	1.7388
5.0	3,600	0.5126	0.0382	0.5122	0.3641	-0.7914	2.3028

Table 4 Results for the secondary pressure losses (shell side)—IESA heat exchanger.

Power (MW)	Flow (gpm)	ΔPP_{rms} (bar)	σ *Psp* (bar)	ΔPP_{max} (bar)	ΔPP_{min} (bar)	Skewness	Kurtosis
---------	1,910	0.0591	5.4 x 10^{-4}	0.0613	0.0578	0.3050	2.8313
---------	1,915	0.0592	7.81 x10^{-4}	0.0620	0.0572	0.5739	3.1727
---------	2,000	0.0634	0.0006	0.0655	0.0613	0.0439	2.8618
---------	2,000	0.0627	0.0007	0.0649	0.0605	0.3413	3.0661
---------	2,100	0.0672	0.0008	0.0697	0.0649	0.0129	2.8817
---------	2,200	0.0714	0.0008	0.0743	0.0691	0.1349	2.5596
---------	2,300	0.0763	0.0010	0.0799	0.0743	1.0892	3.7318
---------	2,430	0.0789	0.0009	0.0814	0.0757	-0.0042	2.4636
---------	2,200	-----	------	-----	----	-----	-----
3.5	2,000	0.0629	00009	0.0632	0.0528	0.1435	3.5345
4.0	2,200	0.0713	0.0009	0.0749	0.0486	0.1762	4.3811
5.0	2,300	0.0753	0.0009	0.0732	0.0641	0.2912	3.5108

Table 5 Results for the shell accelerations—IESA heat exchanger.

Primary flowrate (gpm)	Secondary flowrate (gpm)	$A1_{avg}$ (m/s^2)	$A1_{rms}$ (m/s^2)	$\sigma\ sp$ (m/s^2)	$A1_{max}$ (m/s^2)	$A1_{min}$ (m/s^2)	Skewness	Kurtosis
2,700	1,910	1.7×10^{-5}	17.6×10^{-5}	17.6×10^{-5}	78.1×10^{-5}	-78.1×10^{-5}	-0.0056	3.0138
2,900	1,915	-1.9×10^{-5}	0.0006	0.0006	0.0027	- 0.0026	-0.0054	3.0503
3,000	2,000	-1.8×10^{-5}	0.0005	0.0005	0.0024	- 0.0024	-0.0210	3.0376
3,100	2,000	0.0000	0.0005	0.0005	0.0022	-0.0022	-0.0002	3.0231
3,300	2,100	0.0000	0.0004	0.0004	0.0019	-0.0023	-0.0050	3.1451
3,500	2,200	0.0000	0.0004	0.0004	0.0029	-0.0024	0.0058	3.1670
3,700	2,300	0.0000	0.0004	0.0004	0.0051	-0.0045	-0.0203	3.7948
3,830	2,430	0.0000	0.0005	0.0005	0.0024	-0.0023	0.0012	3.1303
3,500	2,200	----	----	----	----	----	----	----

The result for pressure loss measured in the secondary side was very satisfactory. The flow regime in the tubes is not complex and can be calculated with very good precision with simple empirical correlations (the measured and calculated values were similar).

From shell accelerometer signals was observed that the rms values are very low compared with allowable values from vibrations norms [10]. Comparing with the results from CBC heat exchanger (TC-B) experiments in the same conditions, we can observe that the values were 3,000 times lower. Figs.5 and 6 show the primary and secondary pressure losses versus time for the pump flow coast down experiment.

Fig. 6 shows a reversal flow in the secondary circuit from the IEA-R1. This occurs because there is a water column between the IESA heat exchanger and the B cooling tower. This causes no problem to IEA-R1 reactor installation.

In Fig. 7, the primary flow rate in the flow coast down experiment is shown. This result is very important to the safety operation of the IEA-R1.

These procedures and results are in agreement with similar systems being adopted worldwide and reported in current literature [11, 12].

4. Conclusions

The conducted experiments shown that the IEA-R1 can be operated at 5 MW condition safely and in continuous regime with the new IESA heat exchanger. In relation to the Fig. 7 and to the reactor safety, the authors observe that the 500 gpm flow rate is obtained after 70 s of the pump cutoff. The IEA-R1 reactor has an isolation valve that close the primary fluid circuit for flow rate below 500 gpm.

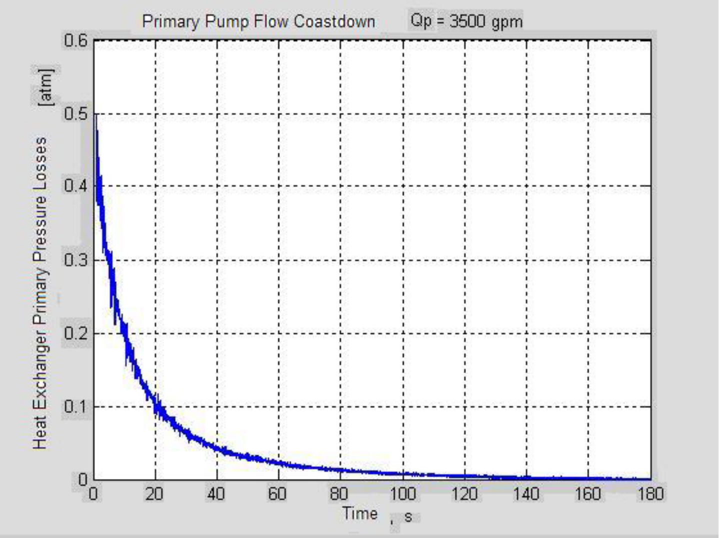

Fig. 5 Primary pump flow coast down. Pressure loss × time.

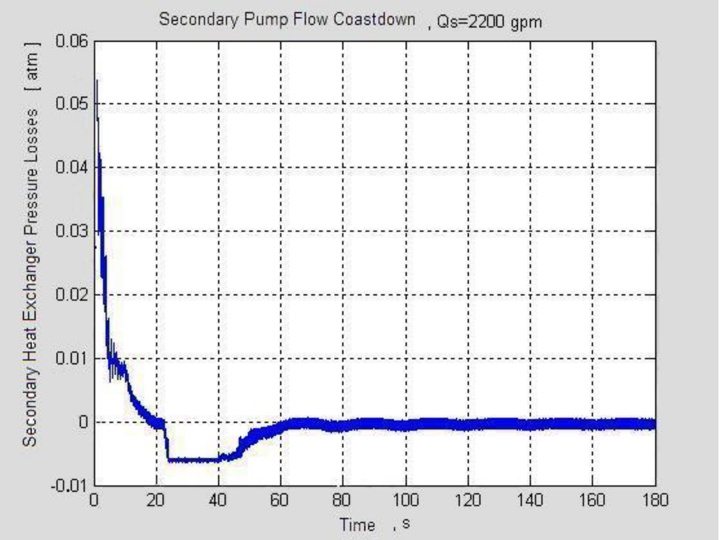

Fig. 6 Secondary pump flow coast down. Pressure loss × time.

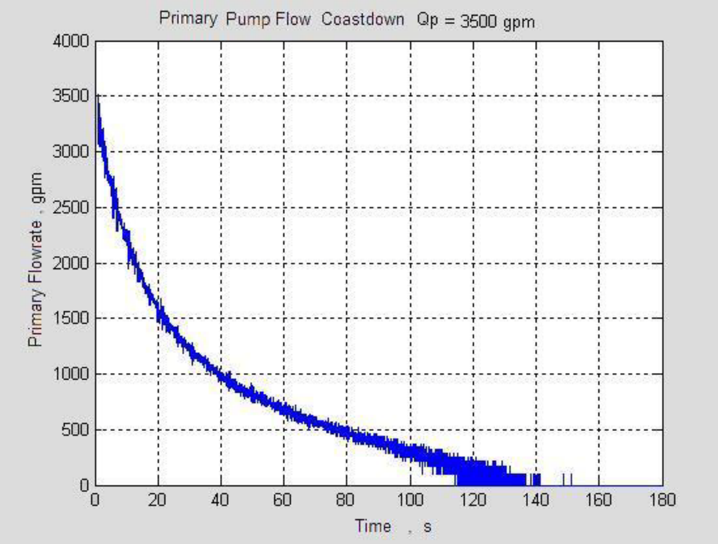

Fig. 7 Primary pump flow coast down, primary flow × time.

So, it can be stated that in 3,500 gpm primary flow rate condition, considering an accidental condition with pump cutoff, the IEA-R1 installation will have enough primary cooling flow to remove residual heat from the reactor during 70 s.

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References

[1] J.A. Perrota, I. Obadia, Multipurpose research reactor, in: LAS-ANS Symposium, Rio de Janeiro, 2010.

[2] C.D. Souza, M.E.C.M. Rostelato, C.A. Zeitune, J.A. Moura, E.S. Moura, K. Fonseca, et al., Analysis of the necessary radioprotection procedures in manufacture of iodine-125 sources used in brachytherapy: A preliminary study, Progress in Nuclear Energy 53 (2011) 66-72.

[3] M.A. Scapin, V.L.R. Salvador, M.E.B. Cotrim, M.A.F. Pires, I.M. Sato, Uncertainty measurement evaluation of WDXRF and EDXRF techniques for the Si and U total determination in U3Si2 nuclear fuel, Journal of Radioanalytical Nuclear Chemistry 287 (2011) 807-811

[4] A.T. Silva, M. Mattar Neto, R.P. Mourão, L.L. Silva, C.C. Lopes, M.C.C. Silva, Options for the interim storage of IEA-R1 research reactor spent fuels, Progress in Nuclear Energy 50 (2008) 836-844.

[5] L.A.A. Terremoto, A.T. Silva, J.E.R. Silva, C.T. Almeida, M.A. Damy, P.E. Umbehaun, et al., Qualification program of research reactor fuels manufactured at IPEN-CNEN/SP, Progress in Nuclear Energy 50 (2008) 795-799.

[6] IAEA—International Atomic Energy Agency, Methodology for the Management of Ageing of Nuclear Power Plant Components Important to Safety, Technical Report 338, IAE- TECDOC-1197, 2001, p. 46.

[7] IAEA—International Atomic Energy Agency, Management of Research Reactor Ageing, Technical Document 792, IAEA-TECDOC-792, 1995, p. 66.

[8] A. Susplugas, E. Greenspan, ENHS reactor power level enhancement possibilities, Progress in Nuclear Energy 50 (2008) 279-285.

[9] A. Baumann, 5 MW IEA-R1 Reactor Heat Exchanger Thermal Design Calculations, Technical Report, IESA Design and Equipments, 2006, p. 40.

[10] A.J. Castro, IEA-R1 Heat Exchangers Vibrations Analysis, Technical Report, 2002, p. 120.

[11] J.W. Bennett, Commissioning of NAA at the new OPAL reactor in Australia, Journal of Radioanalytical and Nuclear Chemistry 278 (2008) 671-673.

[12] G. Ritter, O. Gueton, F. Mellier, D. Beretz, Neutron commissioning in the new CABRI water loop facility, IEEE Transactions on Nuclear Science 57 (2010) 2697-2701.