

# RADIATION FIELD CREATION AT THE ELECTRON LINAC LUE-10 FOR LONG-TERM TESTS OF STRUCTURAL MATERIALS UNDER MOLTEN-SALT REACTOR CONDITIONS

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Long-term (700 hours) corrosion tests of hastelloy-type alloy samples were performed in the  $ZrF_4+NaF$  melt at a temperature of  $650^\circ C$  with the use of the electron linac LUE-10 of power of about 5 kW. To reduce the residual radioactivity of irradiated materials, studies were made into possible ways of a smooth energy shift at the maximum of the electron spectrum to the lower energy region under conditions of a strong current load.

PACS: 29.17.+w

## INTRODUCTION

The radiation tests of structural materials for high-temperature metal-cooled reactors and molten-salt reactors are of crucial importance for the countries oriented at the use of atomic energy.

The radiation conditions that are close to the ones existing in the liquid-salt reactor can be simulated at irradiation of samples to be tested by accelerated electron beams. To perform long-term tests of structural materials in the molten fluoride salts of Zr and Na at a temperature of  $650^\circ C$ , a special test bench was created and installed at the output of the electron linear accelerator LUE-10 [1].

The peculiarity of our approach to the radiation field generation with a simultaneous assurance of the molten salt temperature equal to  $650^\circ C \pm 20^\circ C$  consisted in the fact that the samples under irradiation were heated directly by the electron beam of  $\sim 5$  kW power.

## THE RADIATION TEST BENCH

The samples of structural materials (hastelloy H-type alloys) were placed in individual carbon-carbon containers filled with a molten salt liquid (the molar ratio is 50%  $ZrF_4$ ; 50% NaF). The containers, each measuring  $40 \times 50 \times 50$  mm, were assembled into a single unit consisting of 16 containers. The assembly was 80 mm wide and 400 mm high.

The assembly was put into a sealed stainless steel protective shell cooled with water. The protective shell had a thin input window additionally cooled by an air stream. Using the vacuum pumping system and filling the working volume of the sealed protective shell with inert gas (argon), it was possible to carry out radiation tests of the containers in the inert gas atmosphere. Figure 1 shows the general view of the protective shell comprising the assembly of carbon containers with hastelloy H alloy samples in the molten salts  $ZrF_4$  and NaF. The temperature of the container assembly was controlled by means of three Chromel-Copel thermocouples.

The container assembly was exposed to electrons at the following mode of accelerator LU-10 operation:  
 electron energy at the max. of the spectrum.... 9.6 MeV  
 total average beam current..... 520  $\mu A$

pulse-repetition rate..... 150 GHz  
 effective area of the radiation field.....  $100 \times 400$  mm  
 electron fluence.....  $\sim 10^{19} \text{ cm}^{-2}$   
 irradiation time ..... 700 hours

## Electron irradiation device

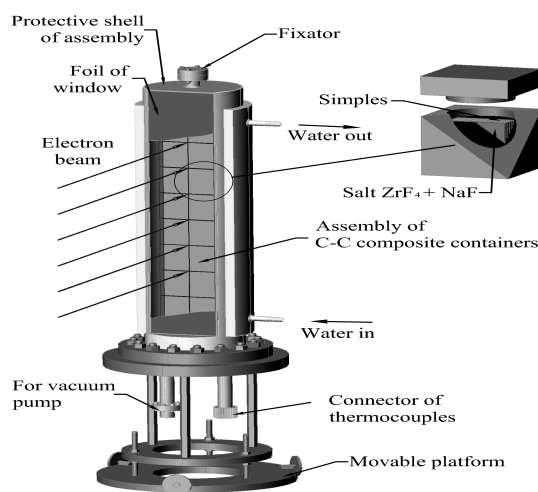


Fig. 1. Container assembly in the protective shell

## CREATION OF THE REQUIRED RADIATION FIELD

Considering that the container assembly (Fig. 1) was  $80 \times 400 \text{ mm}^2$  in size, it was necessary to produce the electron beam with the dimensions corresponding to the size of the assembly to be irradiated.

The radiation field of the required size was formed at the accelerator LUE-10 by means of the scanner that provided a vertical scan of the beam up to the necessary size.

That was attained through the use of a sawtooth and time-evolving magnetic field with an intensity amplitude of  $\sim 700$  Oe and a frequency of 3 Hz. The scan band directly on the exit foil ranges from 18 to 20 cm. In the drift space, the beam irradiates the band  $2L$  in height, depending on the distance  $l$  from the exit foil ( $L = l \text{ tg} \alpha_{\text{max}}$ , where  $\alpha_{\text{max}}$  is the angle of maximum beam deflection from the linear path). The beam current density across is described by the rms sum of total widths  $\sigma$  of normal distributions of electron scattering by the exit

titanium foil (0.005 cm in thickness) of the accelerator, by the aluminum “protective” foil (0.015 cm in thickness) and by the air gap at the distance  $l = 85$  cm from the exit foil:

$$\sigma_{\Sigma} = (\sigma_{Ti}^2 + \sigma_{Al}^2 + \sigma_{air})^{1/2}.$$

The  $\sigma_{\Sigma}$  value has been calculated to be  $\sim 6$  cm. Since the assembly width makes  $2a = 8$  cm, then in the radiation field with the distribution width  $\sigma_{\Sigma} = 6$  cm the ratio of the electron beam density  $I(\mathbf{x})$  at both the edge and the center of the assembly makes  $(I)_{x=a}/(I)_{x=0} = 0.8$  (the nonuniformity being 20%). In view of the fact that the effective width of the region accommodating the samples is 6.5 cm, the nonuniformity across the beam distribution density at assembly irradiation is calculated to be about 10%.

The spatial distribution of the electron beam was measured through obtaining its imprint on the glass of appropriate size, with the following photometering of the darkened area of the glass vertically and across. The photometering was performed with the use of the microphotometer (IFO 451 N880023). To choose the optimum assembly irradiation conditions, the spatial distribution of the electron beam was measured at different distances from the exit window of the accelerator. The experimental data obtained on the spatial distribution of the electron beam in the vertical and horizontal planes have confirmed the correctness of our calculations.

The analysis of the results obtained suggests that it is most reasonable that the assembly should be placed at a distance  $l \sim 850$  mm from the exit window of the accelerator, while the “protective” foil should be at 30 mm from the window.

The present results show that owing to this geometry of irradiation with assembly dimensions of  $80 \times 400$  mm, the beam utilization factor  $\eta$  makes 68% and 53% in the vertical and horizontal planes, respectively. The utilization factor of the total average electron beam on the assembly is equal to  $\eta_{tot} = 36\%$ .

To increase the  $\eta$  value in the vertical plane, the vertical scan may be substantially decreased. In this case, at a nonuniform spatial distribution of 20% on the outermost containers (this is admissible considering that the samples are located at the center of the container),  $\eta_{tot}$  will be 55%.

The irradiation of the assembly with an electron beam having an energy of 9.6 MeV at the maximum of the spectrum was accompanied by the occurrence of residual  $\gamma$ -activity in the irradiated materials [2]. The level of residual activity of an individual container (with the time lag for the decay of short-lived isotopes) is mainly determined by the radiation of  $\gamma$ -lines  $E_{\gamma} = 724.2$  keV and  $E_{\gamma} = 756.72$  keV of the  $^{95}\text{Zr}$  isotope (its half-life being 63.9 days) and by an insignificant contribution from the radiation of  $\gamma$ -lines  $E_{\gamma} = 122$  keV and  $E_{\gamma} = 136.43$  keV of the  $^{57}\text{Co}$  isotope (its half-life being 270 days).

The isotopes  $^{95}\text{Zr}$  and  $^{57}\text{Co}$  are produced in the respective reactions  $^{96}\text{Zr}(\gamma, n)^{95}\text{Zr}$  and  $^{58}\text{Ni}(\gamma, p)^{57}\text{Co}$  (considering that Ni is the base of the hastelloy).

The energy thresholds of the reactions  $^{96}\text{Zr}(\gamma, n)^{95}\text{Zr}$  and  $^{58}\text{Ni}(\gamma, p)^{57}\text{Co}$  are equal to 7.84 and 8.18 MeV, respectively.

To reduce residual activities resulting from the  $(\gamma, n)$  and  $(\gamma, p)$  reactions in the irradiated samples of hastelloy and zirconium salts, it is necessary to consider the possibility of a smooth energy shift at the maximum of the electron spectrum to the lower energy region, i.e., to energies comparable (or lower) with the threshold energies of  $(\gamma, n)$  and  $(\gamma, p)$  reactions on the nuclei of elements entering into the composition of irradiated materials.

The specific character of the LUE-10 accelerator is that its microwave powering is realized by means of two klystrons. A smooth energy variation of the high-current electron accelerator at “current load” conditions has its special features.

Owing to microwave power combining from the two klystrons, and to the energization of klystrons by a highly stable driving generator at the LUE-10, it appears possible to vary smoothly and in a wide range the microwave power in the accelerating waveguide (AW), and hence, the average energy and current of the beam. A fine adjustment of energy is provided by input phasing of one of the klystrons.

Typical beam spectra for four levels of microwave power ( $U_1 < U_2 < U_3 < U_4$ ) in the AW are shown in Fig. 2. With  $U$  decrease, the energy of the principal maximum (PM) of the spectrum smoothly decreases from 10.6 MeV down to 8.4 MeV, and the whole spectrum in the region up to the PM (on its left) shifts to the lower energies without changing its shape, i.e., as a unified whole. After the PM, the shape variation of the spectral curve in the transition from  $U_4$  to  $U_1$  is more substantial, namely, the relative contribution of the high-energy part of the spectrum noticeably decreases. Therefore, it will aid in reducing the level of residual activity due to  $(\gamma, n)$  and  $(\gamma, p)$  reactions on the nuclei of elements entering into the composition of irradiated materials.

The present spectral measurements at different microwave power supply conditions for the AW hold promise for a smooth PM energy adjustment in the range from 10 MeV to 8.0 MeV (see Fig. 2).

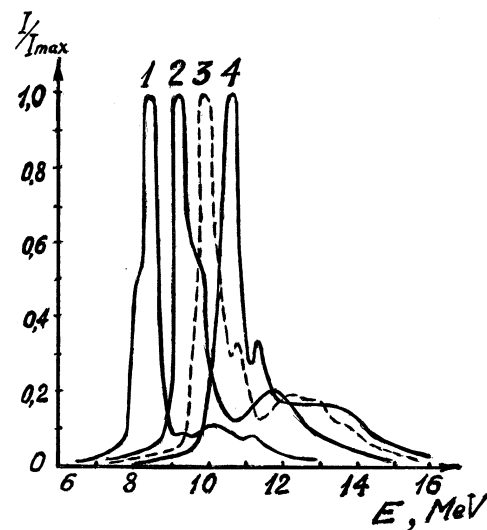


Fig. 2. LUE-10 electron spectra with different energy values at the maximum of the spectrum. 1 – 8.4 MeV, 2 – 9.2 MeV, 3 – 9.9 MeV, 4 – 10.6 MeV

## CONCLUSIONS

1. It has been demonstrated that the electron linear accelerator LUE-10 can provide a long-term (700 hours) continuous irradiation of structural materials with an electron beam of ~5 kW power under conditions approaching those of the molten-salt reactor with a liquid coolant in the form of fluoride salts at a temperature of 650°C.
2. It has been shown that by choosing appropriately the power put into the accelerating section of a high-current accelerator at "current load" conditions, it is possible not only to smoothly reduce the energy value at the maximum of the spectrum down to 8.4 MeV, but also to substantially decrease the high-energy part of the spectrum. This will be favorable for decreasing the level of residual activity due to the ( $\gamma, n$ ) and ( $\gamma, p$ ) reactions on the nuclei of

elements entering into the composition of irradiated materials.

3. The experience gained in radiation studies of structural materials through the use of powerful electron beams will be used in further research and developments in the field of nuclear reactor industry.

## REFERENCES

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## СОЗДАНИЕ НА УСКОРИТЕЛЕ ЛУЭ-10 РАДИАЦИОННОГО ПОЛЯ ДЛЯ ДЛИТЕЛЬНЫХ ИСПЫТАНИЙ КОНСТРУКЦИОННЫХ МАТЕРИАЛОВ В УСЛОВИЯХ СОЛЕВОГО РЕАКТОРА

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На ускорителе электронов ЛУЭ-10 с мощностью  $\cong 5$  кВт проведены долговременные (700 часов) испытания коррозионной стойкости образцов сплава типа Хастеллой Н в расплаве солей  $ZrF_4+NaF$  при температуре 650°C. С целью снижения остаточной радиоактивности облучаемых материалов в условиях сильной подгрузки током изучены возможности плавного сдвига энергии в максимуме спектра электронов в низкоэнергетическую область.

## СТВОРЕННЯ НА ПРИСКОРЮВАЧІ ЛПЕ-10 РАДІАЦІЙНОГО ПОЛЯ ДЛЯ ДОВГОТРИВАЛИХ ВИПРОБУВАНЬ КОНСТРУКЦІЙНИХ МАТЕРІАЛІВ В УМОВАХ СОЛЬОВОГО РЕАКТОРА

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На прискорювачі електронів ЛПЕ-10 з потужністю  $\cong 5$  кВт проведено довготривалі (700 годин) випробування корозійної стійкості зразків сплаву типу Хастеллой Н у розплаві солей  $ZrF_4+NaF$  при температурі 650°C. З метою зниження залишкової радіоактивності опромінених матеріалів в умовах сильного навантаження струмом. вивчено можливості плавного здвигу енергії в максимумі спектру електронів в низькоенергетичну область.