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A POSSIBILITY FOR 300 PBq ^{51}Cr BASED NEUTRINO SOURCE PRODUCTION IN RUSSIAN HEAVY WATER REACTOR L-2: Preprint ITEP 37-98/

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The results of estimation of total activity of 35.53 kg of Cr irradiated in Russian heavy water reactor L-2 are presented. It is shown that total activity 300 PBq (≈ 8 MCi) can be obtained with the lower and higher limits 6 MCi and 10 MCi respectively depending on the conditions of irradiation. Heat removal conditions from the target are estimated. The activity of impurities are calculated. The dependence of activity of impurities on decay time normalised to 1 MCi of radioactive Cr is a function weakly dependent on the conditions of irradiation.. Authors pointed out the possibillity of L-2 reactor to unload the irradiating material step by step in according to the capacity of the operation in the hot chamber.

В работе представлены результаты расчета активности изотопа ^{51}Cr в результате облучения 35.53 кг низкообогащенного ^{50}Cr на российском ректоре Л-2. Показано, что величина активности, которая может быть получена, лежит в пределах от 6 МКи до 10 МКи в зависимости от возможных режимов реактора или ≈ 8 МКи (300 ПБк) – в стандартном режиме. Оценены условия теплосъема с материала мишени и рассчитана γ-активность, образующая на примесных изотопах материала мишени. Показано, что активность этих изотопов, нормированная на 1 МКи основного изотопа, слабо зависит от условий облучения. Указано на важную особенность реактора Л-2 – возможность поэтапной выгрузки облученного материала с учетом производительности горячих камер в случае большого количества стартового материала.

Fig. - 2, ref. - 15 name.

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1. Introduction

The radiochemical solar neutrino experiments running at present (Cl-Ar [1], GALLEX [2], SAGE [3]) observe a deficit of solar neutrino compared to the predictions of solar models [4,5]. Many explanations of this discrepancy have been proposed attributing them either to astrophysics or particle physics. Thus, it is very important to guarantee the trustworthiness of the experimental technique. The direct test of the entire detector procedure is to use an artificial neutrino source (ANS) with well-defined characteristics - intensity, energy, geometry, etc. Both of GALLEX and SAGE which used Ga as a target have already performed this test with ANS based on ^{51}Cr isotope [6,7].

These neutrino sources have been produced from neutron activation of chromium enriched in ^{50}Cr (Table 1). GALLEX Collaboration used a swimming pool reactor in Siloe with 35 MW thermal power and obtains the ^{51}Cr activity equal to (62.5 +/- 0.4) PBq in 1994 and (69.1 + 3.3/-2.1) PBq in the fall of 1995. SAGE Collaboration used fast breeder power reactor BN-350, with 620 MW thermal power and special irradiation assemblies and obtained the ^{51}Cr activity equal to (19.11 +/- 0.22) PBq.

For the next generation of the solar neutrino detectors as real time detectors BOREXINO [8] and LENCSE [9], big scale radiochemical detector GNO [10] the use of an artificial neutrino source with activity more than 100 PBq is necessary. R.Raghavan proposed the ^{51}Cr neutrino source with activity at level 300-370 PBq to calibrate several neutrino detectors placed in the Gran Sasso Laboratory one by one [11].

In this paper we consider the possibility to produce the 300 PBq ^{51}Cr neutrino source in heavy water reactor L-2

2. The requirements for ANS using with solar neutrino detectors

The activity of the ANS required depends on the solar experiment (cross section of the reaction, a density of target material, etc.) and must offer the neutrino flux whose value much more intense than the solar neutrino flux in the detector (for example, A ~ 1 PBq for metallic lithium detector) to get accuracy needed for experiment.

The neutrino energy of the ANS must be higher than the reaction threshold and maximum fits to the solar neutrino spectrum area under study.

The ANS half-life must be more than 2 weeks to provide the operations needed to prepare the ANS [12].

One of the major ANS characteristics is the lack of accompanying high energy γ-rays which is a substantial constraint on the personnel work and the experiment itself, particularly in the case of real time detector [8,9]. The principal sources of γ-rays are:

- decay of the working isotope to excited state which deexcites to the ground state with the emission of high energy γ-rays;
- γ-radiation of the long - lived (a few days) radioactive isotopes produced by activation of certain impurities of starting material, even at concentration of ones at level of ppm (part per million).

Others requirements have been discussed in more details in [12].

A number of K-capture isotopes, ^{51}Cr, ^{65}Zn, and ^{37}Ar, have been suggested [13,14,15] as calibration sources. Based on the above mentioned requirements the best choice of isotope as a neutrino source is ^{51}Cr.

^{51}Cr is produced by neutron captured on ^{50}Cr with high cross sections for thermal and epithermal neutrons (see Table 1). As pointed out in [16] chromium as a starting material must be depleted in ^{53}Cr isotope (because of the high cross section of this isotope) and enriched in ^{50}Cr.

^{51}Cr decays by electron capture with a Q- value of 751 keV to the ground state of ^{51}V (90.14% branching ratio) and to its first excited state (9.86%), which deexcites to the ground state with the emission of a 320 keV γ-rays. The neutrino spectrum consists of four mono-energetic lines (746 keV (81%), 751 keV (9%), 426 keV (9%) and 431 keV (1%). The energy of the dominant 746 keV is very similar to that of the solar neutrinos coming from the electron captured decay of ^{7}Be (E = 862 keV), and 426 keV and 431 keV are close to the energy of the main solar neutrino source, i.e. pp - neutrinos.

The 320 keV γ-radiation is very easy to shield with a few cm of tungsten or lead, and we would like to stress that this γ-ray is particular useful to determine the source activity with direct methods (ionization chamber technique [17], high-resolution γ-spectrometry [18], and Neutron Activation Analysis procedure to determine of ^{51}V concentration as a daughter isotope of ^{51}Cr decay).

Because of high cost of enriched chromium we have to use one which have already been produced before for GALLEX Collaboration (35.6 kg of chromium enriched in ^{50}Cr to 38.6%) or/and SAGE Collaboration (~ 0.8 kg of chromium enriched in ^{50}Cr to 90-93%). But only the ^{50}Cr starting material of GALLEX Collaboration (because of a great deal of ^{50}Cr isotope - 13.8 kg, and low in ^{53}Cr content) is best suited to the production of the ^{51}Cr activity at the level 300 PBq which is needed for the next generation of solar neutrino detector LENCS [9]. This activity made feasibile the high precision measurement of cross section of neutrino reaction and even a use of weak 426 keV neutrino line (for example, to check the transitions to 244 keV and 339 keV isomeric states in ^{160}Tb for the LENCS detector based on ^{160}Gd).

We also would like to point out another advantage of this starting material [19]: ^{50}Cr is in the form of chips with volume ~ 1 mm^3, and therefore, it is easy to homogenize ones after irradiation and carry out the sampling procedure. As a result one can determine the activity of the neutrino source by direct methods and by calorimetry.

The requirements for the production of ≥ 300 PBq neutrino source, i.e. irradiation of a large amount of starting material with a high average thermal neutron-captured cross section in a high average thermal-neutron flux, considerably limit the choices of possible nuclear reactors. From this point of view there are only two reactors in Russia that are best suited to this goal: fast neutron breeder power reactor BN-600 [20] and heavy water reactor L-2 [21]. But if ones takes into account a necessity to unload the starting material at an appropriate time, which not only requires an operating of hot cell, but also a continuous irradiation period that is no more than ~ 2 of the half-life of ^{51}Cr, and the use of ^{50}Cr in the form of chips then our choice actually has to be heavy water reactor L-2 (nick name is "Ludmila", name of heroine of famous Pushkin's poem).

3. Scientific and Technical Aspects of Nuclide Production in Heavy Water Reactor L-2

Reactor L-2 is the last in a series of Heavy Water Reactors [20] (OK-180, OK-190, OK-190M developed and started in the former SU) and it was put into operation in January 1988.

The reactor L-2 was designed for the production of defence materials, however the political and economical circumstances predetermined the necessity of its conversion for the production of radionuclides for civil purposes. Recently reactor L-2, perhaps, can be to the greatest degree called "isotope" reactor for radionuclides production.

The possibilities of L-2 reactor are defined by the facts:

- A square of neutron migration length of heavy water is much more than of that of light water (H_2O) or/and graphite moderator, and so there is a big volume in a core to accommodate a starting material (even many tens of kilograms) . This feature makes possible to locate 36.53 kg of chromium chips in the form of thin layers to avoid the effect of self-shielding of ^{50}Cr.
- There are great number of «free» neutrons in the reactor core which can be used in ^{51}Cr production.

The active zone of L-2 has heterogeneous structure and consists of the lattice of fuel and absorbing channels, loaded with fuel blocks and blocks of absorbers respectively.

In the radial direction the core consists of: 1) zone of a plateau with fuel and absorbing channels, 2) zone of fuel assemblies, 3) reflector, 4) a zone of absorbing assemblies .

Radial power flattening factor about ~ 1.1-1.15 is supported during operation.

Reactor L-2 has only a negative feedback reactivity (power and temperature) effects, that ensures reliable control and high level of safety.

The construction of channels - absorbers allows to perform re-loading at full or a little decreased power level. This is a very important feature for the realisation of programs on different isotope's blocks irradiation (for example, a half-life of ^{51}Cr is 27.7 d, and so irradiation time must be less than 60 days). A number of technical and scientific problems at the performance of a new isotope block is to be solved. First, a necessary temperature mode of target materials is to be provided, that is one of the important conditions, for safe presence of developed blocks in the installation. The design of blocks had to provide the necessary level of heat removal from the targets, that excludes target material phase transformations (melting, in particular for chromium chips also sintering effect etc.), and also its interaction with gas media contained in the block. Secondly, the exception of interaction of a target material with structural coat material of the block. That problem is usually solved by introduction of intermediate fixing elements in designed blocks.

The average over fuel cycle neutron flux of thermal neutrons in the core is insufficient for the production of radionuclides with high activity. The six so-called "neutron traps" were introduced for the local increase of thermal neutron flux in the "plateau" of the reactor core. The content of absorber in central channels of neutron traps is decreased and the content of uranium in fuel channels around is reduced up to 80 % compared to basic value. It allows to increase thermal flux in the neutron trap approximately twice and for example to produce ^{60}Co with specific activity more than 250 Ci/g.

At present the number of developed blocks for radionuclides production includes 38 types, allowing the production over 45 radionuclides in 10 variants of packing, total number of blocks manufactured per one year is about 5000 pieces.

4. ^{51}Cr isotope production

It was proposed to irradiate Cr chips in channels of the core of reactor L-2. ^{50}Cr chips will be placed into cylindrical blocks (the height of blocks will be chosen on the basis of the analysis of the characteristics of containers and parameters of «hot chambers»). These blocks are loaded into absorbing channels of the reactor core in columnar form . The geometry of channels with ^{50}Cr chips is given in Table 2.

The isotopic composition of Cr and cross-sections and resonance integrals are presented in Table 1.

Calculation of ^{51}Cr production were carried out by computer codes TRIFON [22] – simulation of burnup and accumulation of radionulides in «a super-cell», SHERHAN [23] – 3D simulation of L-2 core and ISOTOP – point kinetics code taking account of chain transformations for given thermal neutron flux, spectrum hardness and time schedule.

The estimation of efficiency of irradiation of Cr chips was performed for several variants of loading of chromium in the channel. Three variants were considered: chips were placed in 9, 18, and 36 channels. In the last cases the chromium chips (5th zone, see Table 5) was partially diluted with Al inserts and the effective densities of chips are 1.8 g/cm^3, and 0.9 g/cm^3 respectively.

Two modes of reactor operation were investigated: standard and modified with the reduced inventory of fuel (^{235}U content). The results of simulation of irradiation of ^{50}Cr chips in the core of the reactor L-2 are presented in Table 3.

In the standard mode the total activity of ^{51}Cr equal to 8,5 MCi can be obtained. Depending on the variant of ^{50}Cr loading of channels the activity of ^{51}Cr will make 2.0 MCi /3,7 MCi /6,4 MCi with specific activity 330 Ci /g, 310 Ci /g, and 270 Ci /g respectively (^{50}Cr chips are irradiated in 6 neutron traps). A rest of ^{50}Cr chips are placed in 30 (12 or 3) ordinary irradiation channels and the activity of ^{51}Cr will be reached 6.5 MCi /4.8 MCi /2.1 MCi with specific activity 220 Ci /g, 200 Ci /g, and 180 Ci /g respectively.

At the increase of the reactor pawer by 10 % total activity can be increased up to 9,3 MCi, including that in the neutrons traps up to 7,0 MCi with the specific activity about 300 Ci /g.

In the modified variant with the reduced inventory of fuel at the increase of the reactor power by 10 % the total activity of ^{51}Cr can be increased up to 10,0 MCi with specific activity 270 Ci /g.

5. The thermal characteristics of the channel for irradiation of chromium

The scheme of the channel for irradiation of chromium chips is shown in the Fig. 1. The Cr-target is presented by the cylindrical layer of chromium chips with 4 mm thickness shielded by Al-coating (1 mm) and having bilateral cooling. Energy release in the channel is result of absorption mainly of fission γ-rays energy in the channel components. For standard mode of operations of reactor L-2 the maximum rates of energy release in the channel components are equal:

Al - 5 W/cm^3 ; D_2O - 2,5 W/cm^3; Cr (ρ = 3.6 g/cm^3) - 6,6 W/cm^3

The thermal characteristics of the channel are listed in the Table 4.

Temperature distribution in target was calculated by code which includes the finite-difference method for integrating of one-dimensional heat conduction equation. The temperature distribution is shown in Fig. 2.

6. Impurities and shielding

The most penetrating radiation emitted by ^{51}Cr is the 320 keV γ-line with activity ~ 1 MCi per 10 MCi neutrino source. Due to the interaction length of this γ-line in lead is only 1.1 mm, and only a shielding of several cm of lead is sufficient to satisfy the biological standards for safety. But main problem from this point of view is certain impurities in the enriched chromium with (n,γ) cross sections in the barns range, which will be activated to produce radionuclides with life time more than few days. Part of these radionuclides would be sources of γ-rays of ≥ 1 MeV, with activity at level of Ci. So, the shielding requirements are determined by the impurities with high energy of γ's.

Taking into account of the content of impurities in ^{50}Cr of GALLEX Collaboration [24] (see Table 5) the activity of impurities was calculated for 3 cases corresponding to the following values of total ^{51}Cr activity after irradiation of 35.53 kg of Cr in the reactor L-2 - 6 MCi, 8 MCi and 10 MCi. Reactor L-2 has thermal spectrum of neutrons with low hardness. Therefore at this stage only (n,γ) - reactions were taken into account. Initially calculations were performed by point kinetics code ISOTOP [22] for 1 g of Cr having isotopic content presented in the Table 5. After that the activities were re-normalized to the total activity of Cr equal to 1 MCi and the necessary mass of Cr to be irradiated to get this activity was determined. Corresponding activities are presented in

Table 6. In this normalization the results of impurities activity have very weak dependence on the irradiation conditions (see Table 7).

In the Table 8 the calculated γ- dose rates on the surface of standard container used for storage and transportation of irradiated chromium chips [19] are submitted. The sizes of the Cr source are: diameter of 16 cm, and height of 50 cm. Thickness of tungsten shielding is 8.5 cm.

The characteristics of radionuclides produced by neutron activation of impurities also listed in the Table 8.

All above mentioned requirements regarding to γ-impurities are suited to radiochemical solar experiments. The experiments with real time detectors (for example LENCS) have meet more stringent requirements which are not discussed here.

7. Conclusion

The results of estimation of total activity of ^{50}Cr irradiated in Russian heavy water reactor L-2 are presented. It is shown that total activity 300 PBq (≈ 8 MCi) can be obtained with the lower and higher limits 6 MCi and 10 MCi respectively depending on the conditions of irradiation. As a starting material 35.53 kg of 38% of ^{50}Cr enriched was taken into account. Heat removal conditions from the target are estimated, and lack of sintering effect of chromium chips was demonstrated. The activity of impurities are calculated. The dependence of activity of impurities on decay time normalized to 1 MCi of ^{51}Cr is a function weakly dependent on the conditions of irradiation. Authors pointed out the possibillity of L-2 reactor to unload the starting material step by step in according to the capacity of the operation in the hot chamber.

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Table 1. Isotopic composition of the chromium chips and cross-section sections and resonance integrals.

Isotope	^{52}Cr	^{53}Cr	^{54}Cr	^{50}Cr	^{51}Cr
Contents	60.7 %	0.7 %	0.3	38.6 %	-
Cross-sections, barns	0.76	18.2	0.36	15.9	30.0
Resonance integrals, barns	0.48	8.9	0.18	7.8	
Half-life	stable	stable	stable	stable	27.7 d

Table 2. Geometry of channels with Cr chips. Height of the channel [redacted]

Zone	Thickness, cm	Inner radius, cm	Outer radius, cm	Material
1	1.5	.0000	1.50	Heavy water
2	.100	1.500	1.6	Al
3	.300	1.600	1.90	Heavy water
4	.100	1.90	2.00	Al
5	.400	2.00	2.40	Cr ships
6	.100	2.40	2.50	Al
7	.266	2.50	2.766	Heavy water
8	.174	2.766	2.940	Al
9	2.31	2.940	5.25	Heavy water

Table 3. The main results of modeling of an irradiation of the Cr chips in core heavy water reactor.

Effective density of Cr, g/cm^3	3.6			1.8			0.9		
	Number of channels	Activity, MCi	Specific activity, Ci/g	Number of channels	Activity, MCi	Specific activity, Ci/g	Number of channels	Activity, MCi	Specific activity,Ci/g
Standard mode. The period of an irradiation is 130 days.									
Traps	6	6,4	270	6	3,7	310	6	2,0	330
Core	3	2,1	180	12	4,8	200	30	6,5	220
Total	9	8,5	240	18	8,5	240	36	8,5	240
Standard mode. The period of an irradiation is 50 days (end of cycle).									
Traps	6	5,3	220	6	3,0	250	6	1,6	280
Core	3	1,7	140	12	3,9	160	30	5,2	180
Total	9	7,0	200	18	6,9	200	36	6,8	200
Modified mode with the reduced loading of fuel. The period of an irradiation is 100 days.									
Core	9	7,3	200	18	8,4	240	36	9,1	260
Modified mode with the reduced loading of fuel. The period of an irradiation is 50 days (end of cycle).									
Core	9	6,1	170	18	7,0	200	36	7,5	210

Table 4. The thermal characteristics of the absorbing channel.

Power of channel, kW:	
Al -tubes	5.9
Cr -target	6.2
D_2O - layers of coolant	3.3
total	15.4
Coolant D_2O:	
flow, kg /h	2204
flow rate, m/s	0,7
Temperature of coolant, °C:	
input	30
output	36
Maximum temperatures of target, °C:	
surfaces of coating	34
centre of target	52

Table 5.Content of impurities (ppm) normalised to 1 MCi of ^{51}Cr51 (after irradiation during 130 days).

Content(ppm)	10^6	.005	20.000	50.000	50.000	10.000	5.000	6.000	2.500	20.000	50.000	125.000	15.000
Nuclide	Cr52	Co59	S32	Fe54	Fe58	Na23	Zn64	Cu63	Ni58	Mn55	Si30	Ca44	K41
Content	.607	1.000	.951	.058	.003	1.000	.486	.692	.683	1.000	.031	.021	.067
Nuclide	Cr53		S33					Zn64					
Content	.007		.007										
Nuclide	Cr54		S34										
Content	.003		.042										
Nuclide	Cr50												
Content	.386												
Radio-nuclide	Cr51	Co60	S35	Fe55	Fe59	Na24	Zn65	Zn65	Ni59	Mn56	Si31	Ca45	K42
Half-life, d	2.77 E+01	1.92 E+03	8.75 E+01	9.86 E+02	9.86 E+02	6.24 E-01	2.44 E+02	2.65 E+02	2.74 E+07	1.10 E-01	1.10 E-01	1.64 E+02	5.15 E-01

Table 6. Activity of impurities (Ci) normalised to 1 MCi of ^{51}Cr51 (after irradiation during 130 days).

Case 1. Flux 0.86×10^{14} 1/cm^{2}s, Hardness 0.1, Mass of Cr/1 MCi - 5884.4 g, total activity of 35.53 kg of irradiated Cr - 6 MCi

Radio-nuclide	Cr51	Co60	S35	Fe55	Fe59	Na24	Zn65	Zn65	Ni59	Mn56	Si31	Ca45	K42
Time(d)													
.0	1.00+06	1.39-03	2.98-02	9.15-02	2.52-03	2.01+00	8.73-02	3.60-04	3.67-06	4.34+01	7.57-02	1.94-01	3.02-01
1.0	9.75+05	1.39-03	2.95-02	9.14-02	2.51-03	6.62-01	8.71-02	3.59-04	3.67-06	7.74-02	1.35-04	1.93-01	7.86-02
3.0	9.28+05	1.39-03	2.91-02	9.13-02	2.51-03	7.18-02	8.66-02	3.57-04	3.67-06	2.47-07	4.30-10	1.91-01	5.32-03
5.0	8.82+05	1.39-03	2.86-02	9.12-02	2.51-03	7.79-03	8.61-02	3.55-04	3.67-06	7.85-13	1.37-15	1.89-01	3.60-04
7.0	8.39+05	1.39-03	2.82-02	9.10-02	2.50-03	8.46-04	8.56-02	3.54-04	3.67-06	2.50-18	4.36-21	1.88-01	2.44-05
10.0	7.78+05	1.39-03	2.75-02	9.08-02	2.50-03	3.03-05	8.49-02	3.51-04	3.67-06	1.42-26	2.48-29	1.86-01	4.29-07
15.0	6.87+05	1.38-03	2.64-02	9.05-02	2.49-03	1.17-07	8.37-02	3.46-04	3.67-06	2.57-40	4.48-43	1.82-01	5.11-10
20.0	6.06+05	1.38-03	2.54-02	9.02-02	2.48-03	4.56-10	8.25-02	3.42-04	3.67-06	0.00+00	0.00+00	1.78-01	6.09-13
30.0	4.72+05	1.38-03	2.35-02	8.96-02	2.46-03	6.87-15	8.02-02	3.33-04	3.67-06	0.00+00	0.00+00	1.70-01	8.64-19
40.0	3.67+05	1.37-03	2.17-02	8.89-02	2.45-03	1.03-19	7.79-02	3.24-04	3.67-06	0.00+00	0.00+00	1.63-01	1.23-24

Table 6. Activity of impurities (Ci) normalised to 1 MCi of ^{51}Cr51 (after irradiation during 130 days).

Case 2. Flux 1.15×10^{14} 1/cm^{2}s, Hardness 0.1, Mass of Cr/1 MCi - 4429.6 g and total activity of 35.53 kg of irradiated Cr - 8 MCi.

Time(d)													
R-nucl.	Cr51	Co60	S35	Fe55	Fe59	Na24	Zn65	Zn65	Ni59	Mn56	Si31	Ca45	K42
.0	1.00+06	1.39-03	3.00-02	9.20-02	2.53-03	2.02+00	8.79-02	4.84-04	3.64-06	4.35+01	7.62-02	1.95-01	3.04-01
1.0	9.75+05	1.39-03	2.97-02	9.20-02	2.53-03	6.66-01	8.76-02	4.83-04	3.64-06	7.76-02	1.36-04	1.94-01	7.91-02
3.0	9.28+05	1.39-03	2.93-02	9.19-02	2.53-03	7.23-02	8.71-02	4.81-04	3.64-06	2.47-07	4.33-10	1.92-01	5.35-03
5.0	8.82+05	1.39-03	2.88-02	9.17-02	2.52-03	7.85-03	8.66-02	4.78-04	3.64-06	7.86-13	1.38-15	1.91-01	3.62-04
7.0	8.39+05	1.39-03	2.84-02	9.16-02	2.52-03	8.52-04	8.61-02	4.76-04	3.64-06	2.50-18	4.39-21	1.89-01	2.45-05
10.0	7.78+05	1.39-03	2.77-02	9.14-02	2.51-03	3.04-05	8.54-02	4.72-04	3.64-06	1.42-26	2.49-29	1.87-01	4.32-07
15.0	6.87+05	1.38-03	2.66-02	9.11-02	2.51-03	1.18-07	8.42-02	4.66-04	3.64-06	2.57-40	4.51-43	1.83-01	5.14-10
20.0	6.06+05	1.38-03	2.56-02	9.08-02	2.50-03	4.59-10	8.30-02	4.60-04	3.64-06	0.00+00	0.00+00	1.79-01	6.12-13
30.0	4.72+05	1.38-03	2.36-02	9.01-02	2.48-03	6.91-15	8.07-02	4.48-04	3.64-06	0.00+00	0.00+00	1.72-01	8.69-19
40.0	3.67+05	1.37-03	2.18-02	8.95-02	2.46-03	1.04-19	7.84-02	4.36-04	3.64-06	0.00+00	0.00+00	1.64-01	1.23-24

Table 6. Activity of impurities (Ci) normalised to 1 MCi of ^{51}Cr51 (after irradiation during 130 days).

Case 3. Flux 1.44×10^{14} 1/cm^{2}s, Hardness 0.1, Mass of Cr/1 MCi 3560.9 g, total activity of 35.53 kg of irradiated Cr - 10 MCi

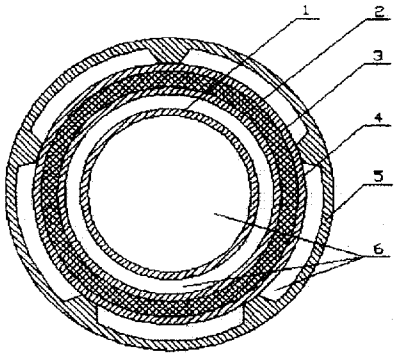
Time(d)													
R-nucl.	Cr51	Co60	S35	Fe55	Fe59	Na24	Zn65	Zn65	Ni59	Mn56	Si31	Ca45	K42
.0	1.00+06	1.39-03	3.02-02	9.26-02	2.55-03	2.03+00	8.84-02	6.10-04	3.61-06	4.36+01	7.67-02	1.96-01	3.06-01
1.0	9.75+05	1.39-03	2.99-02	9.26-02	2.55-03	6.70-01	8.82-02	6.09-04	3.61-06	7.77-02	1.37-04	1.95-01	7.96-02
3.0	9.28+05	1.39-03	2.95-02	9.24-02	2.54-03	7.27-02	8.77-02	6.06-04	3.61-06	2.47-07	4.36-10	1.94-01	5.39-03
5.0	8.82+05	1.39-03	2.90-02	9.23-02	2.54-03	7.90-03	8.72-02	6.02-04	3.61-06	7.88-13	1.39-15	1.92-01	3.64-04
7.0	8.39+05	1.39-03	2.85-02	9.22-02	2.54-03	8.57-04	8.67-02	5.99-04	3.61-06	2.51-18	4.42-21	1.90-01	2.47-05
10.0	7.78+05	1.38-03	2.79-02	9.20-02	2.53-03	3.06-05	8.60-02	5.95-04	3.61-06	1.42-26	2.51-29	1.88-01	4.34-07
15.0	6.87+05	1.38-03	2.68-02	9.16-02	2.52-03	1.19-07	8.47-02	5.87-04	3.61-06	2.58-40	4.54-43	1.84-01	5.17-10
20.0	6.06+05	1.38-03	2.58-02	9.13-02	2.51-03	4.62-10	8.36-02	5.79-04	3.61-06	0.00+00	0.00+00	1.80-01	6.16-13
30.0	4.72+05	1.37-03	2.38-02	9.07-02	2.50-03	6.96-15	8.12-02	5.64-04	3.61-06	0.00+00	0.00+00	1.73-01	8.74-19
40.0	3.67+05	1.37-03	2.20-02	9.00-02	2.48-03	1.05-19	7.89-02	5.50-04	3.61-06	0.00+00	0.00+00	1.66-01	1.24-24

Table 7.Global activity of impurities (Ci) normalised to 1 MCi of ^{51}Cr (irradiation time 130 d). Fl - thermal flux of neutrons, 10^{14} cm^{-2} s^{-1}; Gm - hardness of neutron spectrum.

Mass of Cr (g) to get 1 MCi	→	5880 g	4430 g	3560 g
Decay Time(days)	Fl	8.60-01	1.15+00	1.44+00
	Gm	1.00-01	1.00-01	1.00-01
.0		4.62+01	4.63+01	4.64+01
1.0		1.22+00	1.23+00	1.24+00
3.0		4.79-01	4.83-01	4.86-01
5.0		4.08-01	4.10-01	4.13-01
7.0		3.98-01	4.00-01	4.03-01
10.0		3.93-01	3.96-01	3.98-01
15.0		3.86-01	3.89-01	3.92-01
20.0		3.80-01	3.83-01	3.85-01
30.0		3.68-01	3.70-01	3.73-01
40.0		3.56-01	3.59-01	3.61-01
50.0		3.45-01	3.47-01	3.49-01

Table 8. Gamma dose rates on the surface of standard tungsten container.

Radionuclide	Half- life	γ - rays, Mev	Specific activity of source,Ci/cm^3	Dose rate, mR/h		
				0	1 d	5 d
^{51}Cr	27.7 d	0.32 (10%)	10^3			
^{56}Mn	2.58 h	0.84 (99%) 1.81 (23%) 2.11 (14%)	0.043	414	0.65	
^{24}Na	15 h	1.37 (100%) 2.75 (100%)	$2 \cdot 10^{-3}$	122	40	0.47
^{42}K	12.4 h	1.52 (18%)	$3.1 \cdot 10^{-4}$	0.61		
^{65}Zn	245 d	1.11 (50%)	$8.8 \cdot 10^{-5}$	$2.7 \cdot 10^{-2}$		
^{59}Fe	45 d	1.10 (56%) 1.29 (44%)	$2.5 \cdot 10^{-4}$	$3.2 \cdot 10^{-3}$		
^{60}Co	5.27 y	1.17 (100%) 1.33 (100%)	$1.4 \cdot 10^{-4}$	$5.4 \cdot 10^{-3}$		



1. Inner tube - Ø32×1mm
2. Coating, - Ø40×1mm
3. Cr chips, - Ø48×4mm
4. Coating, - Ø50×1mm
5. Outer tube - Ø58.8× 1.5mm
6. Heavy water

Fig. 1. Cross-sectional view of the channel for irradiation chromium.

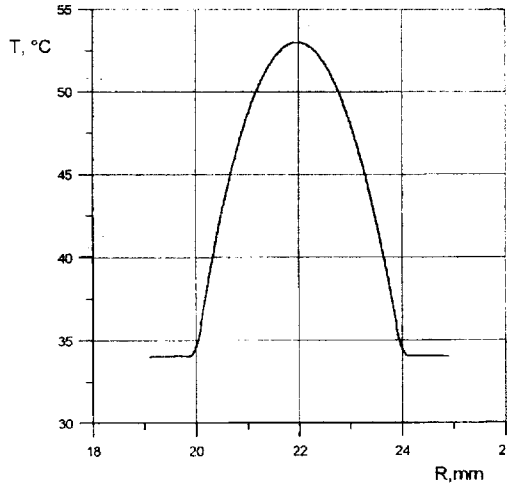


Fig. 2. Temperature distribution in the target.

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