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Conversion of the ARGUS Solution Reactor to LEU Fuel: Results of Feasibility Studies and Schedule

S.V. Myasnikov, A.K. Pavlov, N.V. Petrunin, V.A. Pavshook

Solution Reactors Complex
National Research Centre "Kurchatov Institute"
Akademika Kurchatova sq., 1, 123182, Moscow – Russia

ABSTRACT

ARGUS is a 20 kW solution reactor, which has operated at NRC "Kurchatov Institute" since 1981. Fuel is highly enriched uranyl sulfate solution. The reactor has an inherent safety.

The technology of medical isotopes (^{99}Mo, ^{89}Sr) production at the solution reactor ARGUS with HEU fuel was being developed earlier. The reactor ARGUS conversion is necessary to study the feasibility of isotopes production using LEU fuel. In addition it meets the purposes of the RERTR program.

Feasibility studies of the reactor conversion to LEU-fuel were conducted in cooperation with ANL, the USA in 2010-2012. Positive results of neutron-physical and thermal-hydraulic calculations allowed taking a decision about the reactor conversion. It is planned to produce LEU-fuel using HEU-fuel of the reactor ARGUS. A list of organizational and technical activities during the reactor conversion is determined and a schedule is prepared. The reactor ARGUS conversion will take about 3 years.

1. Introduction

The reactor "ARGUS" is intended for providing nuclear-physical methods of analysis and control and production of radionuclides. Scientific research in the field of neutron activation analysis and neutron radiography has been conducted at the reactor practically since its putting into operation. NRC "KI" is developing the methodical basis of radionuclide production in the solution reactor "Argus". Such a type of the reactor gives a unique possibility of using the whole core for radionuclide production and selectively extracting them from the fuel solution [1, 2].

After conversion, the reactor “ARGUS” purpose will remain the same: to search for the best physical-technical solutions when developing nuclear-physical methods of analysis and control as well as to develop work on production of radionuclides. When the reactor “ARGUS” is converted to low-enriched fuel, one of the main phases of development of the high technology of production of fission radionuclides molybdenum-99, strontium-89 etc will be finished.

2. “Argus” Reactor

″Argus″ is a 20kW homogeneous solution thermal-neutron reactor. The reactor core is the uranyl sulfate water solution enriched up to 90 % in ^{235}U located in a welded cylindrical vessel with a hemispherical bottom and a flat cover. Vertical "dry" channels are installed in the vessel: the central and two symmetric peripheral ones. Control and regulation rods are located in the peripheral channels. The core elements contacting with a fuel solution are made from stainless steel. The reactor vessel is surrounded with a side and bottom graphite reflectors (Fig. 1). There are five vertical channels and one horizontal channel for neutron beam extraction in the reflector.

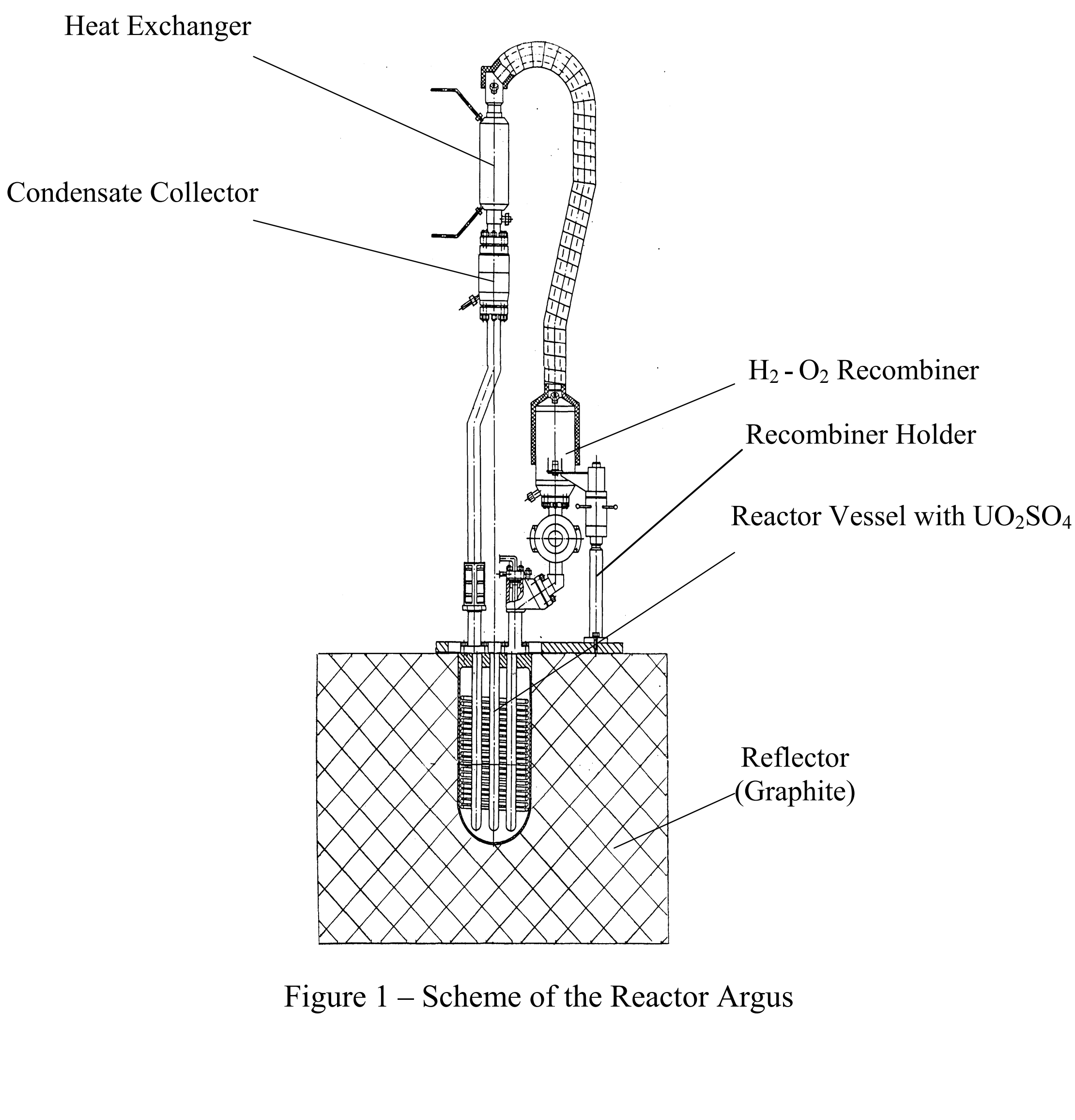

Figure 1 – Scheme of the Reactor Argus

Catalytic Regeneration System (CRS) is meant for regeneration of radiolytic gases hydrogen and oxygen produced in the fuel solution during the reactor operation at power and providing oxygen volume concentration in the free space of the vessel. It forms a closed loop with the core vessel and has the following units: a recombiner; a heat exchanger; a condensate collector (water accumulator); pipelines. The regeneration system is based on the principle of the natural circulation of a gas mixture along the circuit.

Reactor Cooling System is a system with two loops. The first loop is a coil in the reactor vessel. It is connected to the heat exchanger and the compensation tank. The water is pumped through the coil with help of a pump. The second cooling loop removes heat from water of the first loop in the heat exchanger by water.

The solution reactor has an inherent safety determined by the negative power reactivity effect, by the opportunity of cooling down due to the natural air convection, by the lack of local overheatings, low temperature of the solution (up to 90°C) and pressure in the reactor vessel (below the atmospheric one) [3].

3. Brief description of computer programs

Neutronic and thermal-hydraulic models for the HEU and LEU fuel reactor “Argus” were created in course of Feasibility Study performance.

The program MCU is intended for simulating transfer processes of neutrons, photons, electrons and positrons by analog and non-analog Monte-Carlo methods based on estimated nuclear data in the systems with three-dimensional geometry. The program makes it possible to consider the effects of continuous energy change of the particle by collisions as well as continuous and step dependence of sections on energy [4].

The three-dimensional thermal-hydraulic program GIDR-3M operating on the basis of arbitrary (nonorthogonal) finite-element mesh is intended for conducting research and design thermal-physical calculations in the space frames with complex paths of the heat carrier circulation. The program GIDR-3M conducts calculation of velocity vector, temperature, density, pressure, single-phase liquid or gaseous heat carrier, as well as temperature of immobile walls of the construction. The heat transfer process is realized on the basis of the mechanisms: convection, conduction, radiation. The program makes it possible to simulate both stationary and transient processes taking place in different types of constructions [5].

The MCU and GIDR-3M codes is certified in the Scientific and Technical Centre of Nuclear and Radiation Safety of Federal Service of Ecological, Technological and Atomic Supervision.

4. Calculation results

The results of calculations are presented in the Table 1.

Table 1 – Experimental and calculation values of the reactor parameters

Parameter	HEU-fuel		LEU-fuel
	Experiment	Calculation	Calculation
Rated power, kW	20	20	14
Enrichment by uranium-235, %	90	90	19,8
Uranium concentration in the solution, g/l	81,3	81,3	380
Critical charge of uranium-235, kg	1,22	1,22	1,57
Critical volume, l	16,6	16,6	20,9
Operating charge of uranium-235, kg	1,54	1,54	1,88
Operating volume, l	21,1	21,1	24,5
Excess reactivity, $ß_{ef}$	6,3	7,0	4,0
Temperature coefficient of reactivity, β_{ef}/K	минус $5,1 \cdot 10^{-2}$	минус $5,4 \cdot 10^{-2}$	минус $3,9 \cdot 10^{-2}$
Total efficiency of two rods CR and MC, $ß_{ef}$	8,1	8,0	7,5
Efficiency of two rods CP, $ß_{ef}$	7,4	7,3	6,5
Efficiency of two rods EP, $ß_{ef}$	10,0	10,0	8,7
Core subcriticality, ßef	minus 1,8	minus 1,0	minus 3,5
Thermal neutrons flux in CEC, neutron/cm^2·s	$4,1 \cdot 10^{11}$	$5,0 \cdot 10^{11}$	$2,7 \cdot 10^{11}$
Fast neutrons flux in CEC, neutron/cm^2·s	$0,8 \cdot 10^{11}$	$1,3 \cdot 10^{11}$	$0,7 \cdot 10^{11}$

CR – compensating rod

MC – manual control

EP – emergency protection

CEC – central experimental channel

5. Impact of LEU-fuel on the reactor characteristics

Parameters of the cores using low-enriched and highly-enriched fuel as well parameters of solutions themselves have some differences. These differences can influence values of operational parameters of the reactor and functioning of systems and experimental devices of the reactor.

1. Increase of the fuel volume (or reactor core height from 38 to 43 cm) requires change of construction of the several units in the core.

2. Decrease of hydrogen yield value during the reactor operation at power [6] will contribute to decrease of heat removal from solution to the coil due to decrease of the effect of “radiolytic boiling” and decrease of the coolant coil operation efficiency.

3. As solution density and viscosity grows and the effect of “radiolytic boiling” decreases it should be expected that the process of fuel solution mixing and homogenization during the reactor operation at power will deteriorate. Returning from CRS to the core condensate can accumulate in the upper layer of solution. At that, condensate (pH=5.5) and highly-concentrated uranyl sulfate solution can interact what can result in formation of poorly soluble uranium compounds. To make the process of mixing two liquid mediums more efficient we consider it expedient to feed condensate not on the surface of solution as it is conventional at the HEU-reactor but inside solution.

The resultant action of factors: new thermal-physical parameters of fuel solution and parameters of the LEU-fuel core itself (density, heat capacity, radiolytic gases formation rate, new height of solution and other) will lead to degradation of the cooling system. Analysis of the cooling system functioning shows that it is advisable to increase efficiency of the cooling system by way of including a system with a water chiller in the second cooling loop. It will permit to decrease the coolant temperature to 10°C and increase up to 16-18 kW.

6. Procedure of the conversion

Two scenarios of the reactor “Argus” conversion to LEU-fuel were considered. The first one is replacement of HEU-fuel by newly-produced new LEU-fuel. The second one is production of LEU-fuel using HEU-fuel of the reactor “Argus”. The second variant was chosen. There are data demonstrating the possibility in principle of the reactor conversion to LEU-fuel using 100% of HEU-fuel applying different components provided in Table 2.

Table 2 – Physical characteristics of solutions-components and resulting LEU-solution

Parameter	HEU-fuel (in the reactor)	Reserve fuel	Fuel of natural enrichment	LEU-fuel
Uranium mass, g	1711	321	7468	9500
Uranium-235 mass, g	1540	289	52	1881
Volume, l	9,22	0,64	15,14	~25
Concentration, g/l	185,6	502	493	380
Enrichment, %	90	90	0,7	19,8

It is necessary to carry out the following technical activities to convert the reactor to LEU-fuel:

- to measure HEU-fuel volume and to sample HEU-fuel for preliminary analysis of its characteristics;

- to increase HEU-fuel concentration to the design value (evaporation);

- to produce LEU-fuel using HEU-fuel in reactor, reserve HEU-fuel and uranium with natural enrichment.

- to load LEU-fuel to the reactor.

Increase of the reactor “Argus” HEU-fuel concentration to the design value is realized directly in the reactor vessel. A thermoelectric heater is mounted on the outer surface of the reactor cooling system pipeline. Such a heater makes it possible to heat the solution up to 50…60˚C and fill the radiolysis products regeneration system condensate collector with evaporated water making a part of fuel solution. Water is poured out of the condensate collector to reservoirs; after that water amount is measured.

The HEU-solution should be poured out of the reactor vessel with help of the upgraded Fuel Loading System into 6 reservoirs. Necessary quantities of additional solution with nuclear material natural enrichment (0,7%) should be produced to get LEU-fuel of the reactor “Argus”. After LEU-fuel is obtained samples are taken from each reservoir to determine solution parameters (enrichment, concentration, acidity).

Temporary storage, transportation and handling of the fuel solution should be realized meeting requirements on nuclear, radiation safety and requirements on non-proliferation of nuclear materials. Temporary storage of solutions should be realized in transport packing complexes (containers).

The reactor vessel is charged with HEU-fuel with help of Fuel Loading System meeting requirements of nuclear and radiation safety.

7. Conversion schedule

The main stages of the conversion and schedule are given in the Table 3.

Table 3 - The main stages of the conversion and schedule.

Item	Description	Term
1	Program and the schedule of the reactor conversion to LEU-fuel	Nov. 2012
2	Safety Justification Report for LEU-fuel reactor “Argus”	Jan. 2013
3	Activities associated with necessary changes for conversion	
3.1	Development of requirements specifications for reactor, temporary fuel storage, start-up equipment, and TPC	Mar. 2013
3.2	Development of engineering, working, maintenance, methodical and other documentation	May. 2013
3.3	Manufacture and tests of nonstandard equipment. Updating of the engineering documentation	Sep. 2013
4	Equipment of the room, development and creation of the device for temporary storage of the fuel solution	
4.1	Development of requirements specification for the device for fuel solution temporary storage	Jul. 2013

Item	Description	Term
4.2	Installation, testing, and regulatory approval of equipment related to the device for fuel solution temporary storage	Nov. 2013
5	Bringing the reactor into safe subcritical condition. Partial evaporation of fuel solution water.	Jan. 2014
6	Installation, regulation, and precommissioning for necessary changes	Jul. 2014
7	Preparation and certification of the LEU-fuel:	May. 2014
8	Physical start-up of reactor (loading the HEU-fuel)	Sep. 2014
9	Power start-up of reactor	Nov. 2014
10	Establishing operating parameters and experiment study methods	Jan. 2015
11	Correction reactor documentation	Apr.2015
12	Obtaining reactor operating permission	Jun. 2015
13	Putting the LEU-fuel reactor "Argus" into trial operation	Jun. 2015

The cost of the conversion is estimated in $2 million.

8. Conclusion

As a result of Feasibility Study it was shown that it is feasible in principle to convert the reactor. The power decreases to 14 kW at that. If the reactor cooling system is modernized it can increase up to 16-18 kW.

Necessary activities to enable the "Argus" reactor conversion were analyzed and their cost was estimated. The analysis showed that the work on conversion can be fulfilled within three years. At that, justification of the reactor safety and development of the project documentation in connection with the changes and the conversion as a whole is conducted the first year. Mounting, precommissioning and commissioning of the mounted equipment is realized the second year. Fuel replacement, getting of neutron-physical and operating parameters of the reactor with LEU-fuel and putting of the reactor into operation is conducted the third year.

Acknowledgement

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