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State of Work on Calculation Studies of the MIR Reactor Conversion

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ABSTRACT

In 2011, within the framework of the RERTR program, the justifying calculations of the possibility of the MIR test reactor conversion was started. This paper presents the preliminary results of the calculation analysis of neutron-physical characteristics of the MIR reactor core with 90%-enriched uranium dioxide fuel as well as several core options with low-enriched uranium dioxide and high-density metallic dispersed U-Mo fuel. The calculations showed that the dispersed U9%Mo-based fuel is more preferable for the MIR reactor conversion than uranium dioxide. To retain the neutron-physical characteristics of the MIR reactor with low-enriched fuel, it is necessary to increase the fuel layer thickness in fuel rods from 0.56 mm up to 0.94 mm. Besides, it is expedient to increase the quantity of fuel rods in the assembly from 4 up to 6.
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1. Introduction

The test MIR reactor with the rated power of 100MW was commissioned in 1967 at RIAR (Dimitrovgrad, Ulyanovsk region, Russia). The reactor has loop facilities with different coolant types and is designed for testing different fuel types of nuclear reactors under conditions simulating the steady-state and transient operating modes as well as some design-basis accidents.

At present, the driver fuel assemblies (FA) use 90%-enriched uranium dioxide. For the reactor conversion, low-enriched uranium dioxide and U-Mo alloy are considered, one of the main requirements being the retaining the overall dimensions of the FA. This requirement is stipulated by the fact that a new FA could not cause the subsequent design changes of the reactor.

The objective of the research is to assess the neutron-physical and technical-economical characteristics of the MIR reactor core with different fuel types in the process of its burnup. The core with highly-enriched uranium (HEU) fuel based on uranium dioxide is accepted as the base option. The cores with low-enriched uranium (LEU) based on uranium dioxide and U+9Mo alloy are considered as the alternative.

The base option of the core considers a 4-tube FA with the thickness of the fuel meat of 0.56 mm. When converting to the LEU fuel, the fuel rods with the fuel meat thickness increased up to 0.94 mm are considered as a measure to increase the FA uranium capacity. For this purpose, a 6-tube FA with additional internal fuel rods Ø34x2 mm and Ø25x2 mm are considered.

The feasibility was conducted by the specially developed approximation equation. The equation was tested by the precision program complex calculation results [1] and operating data of the MIR reactor.

2. MIR reactor specifications

By its physical essence, the MIR reactor is a thermal heterogeneous reactor with metal beryllium moderator and reflector [2]. The main reactor specifications are presented in Tab.1.

Table 1 - Main MIR reactor specifications

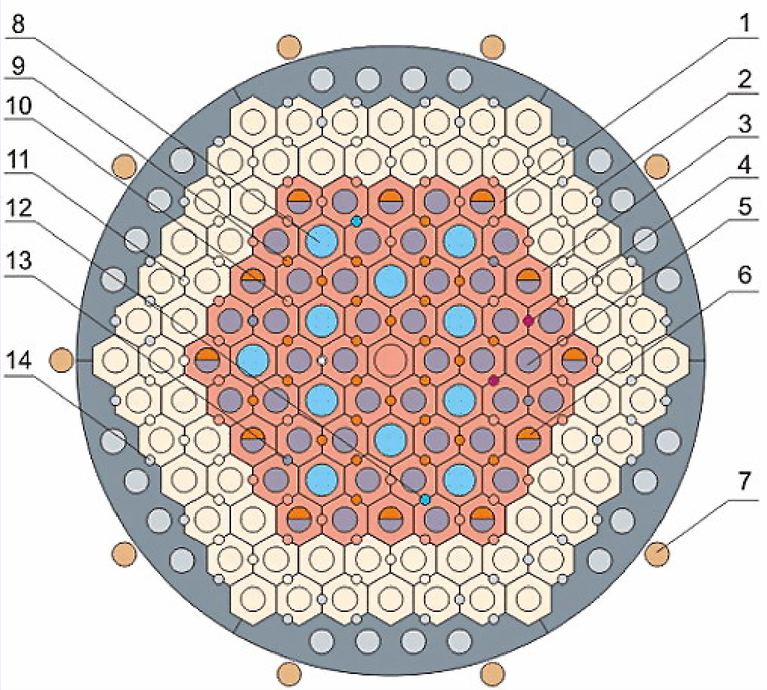
Characteristics	Value
Maximum thermal power, MW	100
Thermal neutrons flux in experimental channels, $cm^{-2} \cdot s^{-1}$	$\leq 5 \cdot 10^{14}$
Minimum critical loading of ^{235}U, g	2080
Uranium enrichment in ^{235}U, %	90
Core height, mm	1000
Diameter of the driver fuel channel, mm	78
Maximum diameter of the loop channel, mm	148.5
Moderator and reflector	beryllium
Primary circuit coolant	water
Coolant pressure at the core inlet, MPa	1.25
Coolant temperature at the core inlet	≤70
Coolant temperature at the core outlet, °C	≤ 98
Quantity of channels for driver FAs	≤58
Quantity of shim rods	22
Quantity of emergency rods	6
Quantity of automatic control rods	2
Average heat rate in the core, kW/l	85.5
Quantity of the loop channels	11
Average burnup in the spent FA, %	≤60
Duration of the cycle, day	≤40

The reactor cross-section with the main core elements is shown in Fig.1. By its design peculiarities, it is a channel one and is installed into the water pool. Fig.2 depicts the reactor longitude cross-section. Such a design solution allowed combination of the main advantages of the pool and channel reactors.

Firstly, the reactor submerged in the water pool is potentially less dangerous in the case of accident, as the core, driver channels, inlet and outlet pipelines and collectors are under water.

Secondly, all the loading-reloading operations of the fuel and core units conducted under water and can be visually controlled. This technical solution simplifies the technology of conducting this work, reduces the radiation background and correspondingly decreases the risk of personnel radiation over-exposure.

Thirdly, use of the channel design with a hard moderator allowed increase of the distance between the cells for the driver and experimental channels, placing the driver and loop channels heads and provision of the access to the experimental channels and the possibility of their tool equipping, installation of the adequate quantity of the control rods to create and maintain the specified irradiation conditions in the experimental channels.



1 – Core Be-block
2 – Reflector Be-block
13 – Control rod tube with a plug
14 – Al-plug3 – Loop channel Be-block
4 – Automatic control rod
5 – Driver FA
6 – Movable FA
7 – Ionizing chamber
8 – Loop channel
9 – Shim/Emergency control rod
10 – Core Be-plug
11 – Reflector Be-plug
12 – Control rod tube

Fig.1 Reactor core arrangement

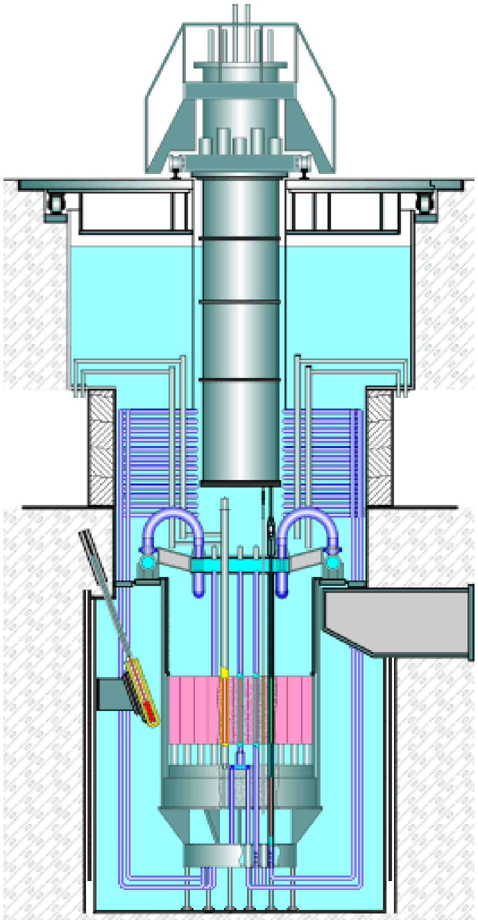
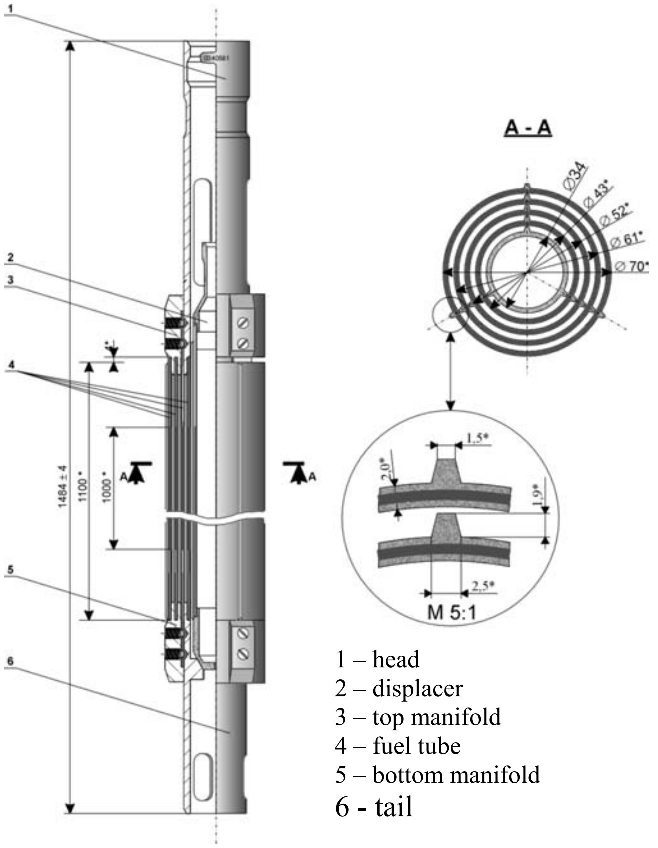


Fig. 2. MIR reactor longitude cross-cut

The core skeleton is arranged of hexahedral beryllium blocks with the across flats dimension of 148.5 mm by the triangular lattice with the gaps between them of 1.5 mm each. In the central axial holes of the blocks, there are channels to place driver FA (49 pc.) and experimental devices (11 pc.); and channels for control rods are located in the holes between the adjacent beryllium blocks. Each experimental loop channel is surrounded by 6 channels with the driver FA and (4÷5) control rods. Varying the driver FA burnup and location of the control rods around the loop provides the possibility of simultaneous maintaining the test conditions practically in all loop channels.

The FA consists of 4 tubular elements [3]. The fuel column with the rated thickness of 0.56 mm consisting of uranium dioxide particles dispersed in the aluminum matrix, the rated thickness of the claddings made of the SAV-6 aluminum alloy is 0.72 mm. Fig. 3 presents the draft of the MIR reactor fuel assembly.

3. Choice of the reference parameters and criteria to compare the characteristics of HEU and LEU fuel based cores



1 – head
2 – displacer
3 – top manifold
4 – fuel tube
5 – bottom manifold
6 - tail

Fig.3. MIR reactor FA

In practice, the operating mode and characteristics of the test reactor core can change considerably from campaign to campaign. They are mainly determined by the program of irradiation in the core and experimental channels.

For example, the burnup at the beginning of the campaign can make up 26-30%, at the end of the campaign it can be 33-40%, in the unloaded FA – 55-60%. In this case the initial reactivity margin can vary in the range of 9-13% and campaign duration - from 20 up to 35 days. The number of reloaded FA can, correspondingly, change from ~ 2 up to 7. The reactor can operate not till full exhaustion of the reactivity margin, which can make up from 3 up to 6 βeff by the end of the campaign. Under such indefinite conditions, cores with HEU and LEU fuel will strongly differ by the physical characteristics and fuel consumption.

However, for the comparative analysis of the characteristics of the core with different enrichment fuel it is required to accept some comparison conditions (reference conditions), which could allow obtaining the objective picture of the advantages and disadvantages of this or that option.

Let assume that the comparison will be conducted:

- equal reactor power;
- equal duration of the reactor average cycle and campaign;
- the reactor operates in the steady mode of partial fuel reloading;
- the reactivity margin at the end of the cycle should be equal;
- equal duration of the annual preventive repair;
- the equal duration of the reactor shut-downs between the cycles.

Under these conditions, the average reactor output will be equal during the cycle and year for the cores with HEU and LEU fuel, and differences of the cores characteristics will be exclusively stipulated by differences in the enrichment, density and material composition of the applied fuel:

- various reactivity margin at the beginning of the cycle due to the various rate of reactivity loss because of various density of 235U fuel;
- various number of the reloaded FAs at the end of the cycle due to the various values of reactivity margin at the beginning of the cycle and physical efficiency of FA;

- various time of FA operation (fuel campaign) and, correspondingly, fuel burnup in the unloaded assemblies due to various amount of 235U in FA;

- as a result: various annual consumption of uranium and FAs;

- various neutron flux density in the core and experimental channels due to various density of the fuel in 235U and 238U, etc.

Since the comparison should be conducted by the sufficiently wide list of parameters (neutron-physical and thermo-hydraulic characteristics of the core, experimental channels, technical&economical indices of the reactor, etc.), here the analysis, selection and specification of the parameters for comparison are also necessary.

Tab. 2 presents the main characteristics for comparison of the cores with different fuel types.

Table 2 – Reference parameters of the cores

No.	**Parameter**
1	Density of the fuel meat in U, g/cm
2	Volume fraction of the fuel in the composition, %
3	Amount of ^{235}U in FA, kg
4	Burnup, rel. uni
5	Reactivity margin, %
6	Rate of reactivity loss, 10^{-3}/MW· day
7	Poisoning effect, %
8	Reactivity margin for burnup, %
9	Average burnup during cycle, rel. unit
10	Average burnup at the end of the cycle, rel. unit
11	Average burnup in the unloaded FA, rel. unit
12	Quantity of the spent FA, pc.
13	Fuel campaign, day
14	Accumulation of fission products in the unloaded FA, g
15	Number of shut-downs for reloading per year
16	Annual demand for FA
17	Annual consumption of uranium, kg
18	Coefficient of reactor time using during year,%
19	Fast neutron fluence on the cladding of the experimental fuel in the loop channel, cm^{-2}
20.	Maximum coolant flow rate, m^3/hour - through the core - through the driver FA
21	Maximum velocity of the coolant in the driver FA, m/s
22	Maximum power of the driver FA, MW
23	Pressure drop in the core, MPa

In this paper the consideration is only limited to the tubular-design fuel elements. If the fuel elements dimensions are changed (which is assumed), it can be expected that the hydraulic characteristics of the core will change negligibly. I.e. the thermo-hydraulic characteristics in this case will not be determining ones in differences between the cores with HEU and LEU fuel.

Thus, the significant parameters for comparison will be the irradiation conditions in the experimental channel and fuel expenses. The productivity measure of the test reactor, the products of which are neutrons, can be the annual fluence on the fuel elements claddings placed in loop channels multiplied by the volume of these channels.

Since the cores with approximately equal experimental volumes are considered, the productivity indices for their comparison will be considered the annual fast neutron fluence:

$$F = \varphi_f \cdot T \cdot n_c \tag{1}$$

Where: φ_f - fast neutron flux on the fuel elements claddings in the experimental channel, cm^{-2}s^{-1};

T – duration of reactor cycle, day;

n_c – number of reactor cycles per year.

Let us consider the annual consumption of FA or quantity of spent FA – N, as the expense indices. Thus, the objective function (quality criterion of the fuel cycle) in the task for the maximum in our case becomes:

$$K_1 = \frac{\tilde{\Phi}}{\tilde{N}} \tag{2}$$

Where: $\tilde{\Phi} = \frac{\Phi}{\Phi_0} = \frac{\varphi_f}{\varphi_{f0}} \cdot \frac{T}{T_0} \cdot \frac{n_c}{n_{c0}}$ - ratio of annual fast neutron fluence on the experimental fuel elements cladding in the experimental channel LEU fuel to the analogous value for the core with HEU fuel. Since the comparison is conducted at the same duration of the reactor campaign and, correspondingly, the same number of shut-downs for reloading per year, then $\tilde{\Phi} = \frac{\varphi_f}{\varphi_{f0}}$;

$\tilde{N} = \frac{N}{N_0}$ - ratio of annual FA consumption for the core with LEU fuel to the corresponding value for the core with HEU fuel.

The cost of reprocessing of the spent fuel depends not only on the number of assemblies, but also on the mass of uranium contained in FA. So it is expedient to introduce the additional criterion K_2 taking into account this circumstance:

$$K_2 = \frac{\tilde{\Phi}}{\sqrt{(\tilde{N}\tilde{G})}}, \tag{3}$$

here: $\overline{G}$ - ratio of the annual uranium consumption of the reactor with LEU fuel to the corresponding value for HEU fuel.

4. Comparison of the characteristics of the core based on HEU and LEU fuel

4.1 Initial data of the core with HEU and LEU-based fuel

The initial data used in the calculated assessments for comparison of the characteristics of the cores with different fuel types are presented in Tab.3.

Table 3 – Initial data of the core based on HEU and LEU fuel for analysis

Parameter	Value		
	HEU	LEU UO_2	LEU U-Mo
Thickness of the fuel meat, mm	0.56	0.94	0.56/0.94
Thickness of the fuel rod cladding, mm	0.72	0.53	0.72/0.53
Quantity of fuel rods in FA	4	4/6	4/6
Size of the displacer in FA, mm	34x2	34x2/16x2	16x2/34x2
Density of the meat in uranium, g/cm^3	1.03	2.90	5.0
Volume fraction of the fuel in the fuel meat, rel. unit	0.112	0.317	0.229
Enrichment, rel. unit	0.9	0.197	0.197
Duration of the reactor campaign, day	14	14	14
Reactor power, MW	40	40	40
Burnup of U-235 at the beginning of the cycle, %	30	x	x
Burnup of U-235 at the end of the cycle, %	34.7	x	x
Weight fraction of uranium in the fuel, rel. unit	0.88	0.88	0.90
Fuel density, g/cm^3	10.4	10.4	17.0

x – TBD

The reactor power, campaign duration, fuel burnup for HEU fuel were obtained as the result of analysis of the operating modes of the MIR reactor during 7 years. The thickness of the fuel element fuel column with LEU fuel was accepted equal to the thickness of the fuel column of the MR type experimental fuel elements with oxide fuel previously fabricated by NCCP for reactor tests at RIAR.

4.2 The core with LEU uranium dioxide-based fuel

The comparative characteristics of the cores with HEU and LEU fuel are presented in Tab.4.

It is clear from Tab. 4 that increase of the U density of the LEU fuel column in up to 3 g/cm^3 and thickness of the fuel column up to 0.94mm in the 4-tube assembly allow retaining the loading of U-235 into FA for as well as for HEU. In this case, however, the required reactivity margin (12.6%) is provided at the less fuel burnup (18% in LEU against 30% in the base HEU variant). As the result the quantity of the reloaded FA, annual consumption of assemblies is increased by a factor of 1.5 and uranium by a factor of 7.3. The both criteria are considerably less than unity.

The increase of the fuel elements quantity in FA to six allows increase of the loading of U-235 into FA by a factor of 1.33 for non-irradiated fuel and bringing the burnup to the values close to the base HEU variant (~30%). The quantity of the reloaded FA and annual demand for assemblies decrease by about 20% as compared to the base variant, uranium consumption exceeds the corresponding value by a factor of 4.6.

Table 4 – Comparative characteristics of the cores with oxide fuel

Parameter	Value		
	HEU	LEU UO$_2$	
Quantity of fuel rods in FA, pc.	4	4	6
Thickness of the meat, mm	0.56	0.94	0.94
Density of uranium in the fuel meat, g/cm^3	1.027	3	3
Volume fraction of the fuel in the fuel meat	0.112	0.328	0.328
Mass of U-235 in FA, kg			
- fresh fuel	0.356	0.380	0.476
- at the beginning of the cycle	0.249	0.312	0.333
- at the end of the cycle	0.232	0.295	0.316
Burnup, rel. unit			
- at the beginning of the cycle	0.30	0.18	0.30
- at the end of the cycle	0.347	0.225	0.336
Rate of the reactivity loss, 10^{-3} %/MW day	3.44	2.84	2.63
Poisoning effect, %	1.54	1.30	1.51
Reactivity, %:			
- fresh fuel	20.8	17.5	20.9
- at the beginning of the cycle	13.2	12.6	12.7
Accumulation of fission products in the spent FA, g/cm^3	0.46	0.18	0.29
Quantity of the reloaded FAs per cycle	3.6	5.4	2.8
Annual consumption of FAs	58.7	87.7	44.6
Annual consumption of uranium, kg	23.2	169.2	107.9
Criterion К$_1$	1.0	0.64	1.25
Criterion К$_2$	1.0	0.29	0.51

4.3 The core with fuel based on U-Mo alloy

The characteristics of the cores with U-Mo LEU fuel are presented in Tab. 5. The analysis of the data from Tab.5 shows that application of U-Mo LEU fuel with the density in uranium 5 g/cm^3 in the standard design FA considerably worsens the physical and technical-economical characteristics of the core. With increasing the thickness of the fuel column up to 0.94mm the core parameters are improved: fuel burnup increases up to 50%, annual demand for FA decreases by a factor of 2.8, annual consumption of uranium remains by a factor of 3 greater than in the base variant.

Application of 6-tube FA leads to further improvement of the reactor characteristics. The fuel burnup increases up to 60%, annual demand for FA becomes by a factor of 4 lower that in the base variant. The consumption of uranium remains in this case by a factor of 2.6 higher, but both quality criteria become more than unity.

There is a separate task to justify the performance of the optimal design fuel rods under different MIR reactor operating modes. This is related to the fact that increase of the thickness of the fuel layer in fuel rods leads to decrease of the cladding thickness, which, in its turn, reduces their operating reliability. Besides, when using the second option of increasing the quantity of rods from 4 to 6 in the fuel assembly, the volume of the free cavity in the center of the assembly considerably decreases, that can be used for materials irradiation.

Table 5 – Comparative characteristics of the cores with U-Mo fuel

Parameter	Value			
	HEU	LEU U-9%Mo		
Quantity of fuel rods in FA, pc.	4	4	4	6
Thickness of the fuel meat, mm	0.56	0.56	0.94	0.94
Density of uranium in the fuel meat, g/cm^3	1.027	5	5	5
Volume fraction of the fuel in the fuel meat	0.112	0.326	0.326	0.326
Mass of U-235 in FA, kg				
- fresh fuel	0.356	0.379	0.634	0.794
- at the beginning of the cycle	0.249	0.326	0.320	0.344
- at the end of the cycle	0.232	0.310	0.303	0.327
Burnup, rel. unit				
- at the beginning of the cycle	0.30	0.14	0.50	0.57
- at the end of the campaign	0.347	0.184	0.526	0.591
Rate of the reactivity loss, 10^{-3} %/MW day	3.44	2.72	2.66	2.43
Poisoning effect, %	1.54	1.24	2.03	2.33
Reactivity, %:				
- fresh fuel	20.8	16.3	26.4	28.4
- at the beginning of the campaign	13.2	12.5	13.2	13.4
Accumulation of fission products in the spent FA, g/cm^3	0.46	0.24	0.76	0.87
Quantity of the reloaded FA per cycle	3.6	6.8	1.3	0.9
Annual consumption of FA	58.7	110.3	21	14.7
Annual consumption of uranium, kg	23.2	212.4	67.5	59.5
Criterion K_1	1.0	0.51	2.66	3.78
Criterion K_2	1.0	0.23	0.93	1.18

Conclusion

1. The preliminary calculated investigations of the neutron-physical characteristics of the MIR reactor cores with oxide HEU fuel and different LEU fuel types were conducted for selection of the design execution of the fuel assembly.

2. The optimization task for the objective functional maximum was formulated. It was shown that when using the tube design fuel elements, application of the high-density LEU without introducing the constructive changes for increasing the uranium capacity of fuel elements leads to considerable worsening of the consumer characteristics of the core.

3. Low-enriched uranium dioxide is essentially less effective than the U-Mo alloy. In the case of applying the high-density fuel based on U-9%Mo alloy increasing the thickness of the fuel layer in tubular fuel elements without change of their quantity and FA overall dimensions it is possible to convert the MIR reactor without loss of the consumer characteristics.

4. Thus, the conducted assessments allowed determination of the optimization trends of fuel elements – increase of the thickness of the U-9%Mo fuel layer in tubes and increase of the quantity of tubes from 4 to 6 in the fuel assembly. The next stage of the work should be the specifying calculations by the precision programs.

5. There is a separate task to justify the performance of the optimal design fuel tubes under different MIR reactor operating modes. This is related to the fact that increase of the thickness of the fuel layer in fuel rods leads to decrease of the cladding thickness, which, in its turn, reduces their operating reliability.

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