THERMOPHYSICAL INSTRUMENTS FOR NON-DESTRUCTIVE EXAMINATION OF TIGHTNESS AND INTERNAL GAS PRESSURE OF IRRADIATED POWER REACTOR FUEL RODS

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Abstract

The developed thermophysical method and technical instruments for non-destructive leak-tightness and gas pressure inspection inside irradiated power reactor fuel rods and FAs under poolside and hot cell conditions are described. The method of gas pressure measuring based on the examination of parameters of thermal convection that aroused in gas volume of rod plenum by special technical instruments. The developed method and technique allows accurate value determination of not only one of the main critical rod parameters, namely total internal gas pressure, that forms rod mean life in the reactor core, but also the partial pressure of every main constituent of gaseous mixture inside irradiated fuel rod, that provides the feasibility of authentic and reliable leak-tightness detection. The described techniques were experimentally checked during the examination of all types power reactor fuel rods existing in Russia (WWER, BN, RBMK) and could form the basis for new technique development for non-destructive examination of PWR (and other) type rods and FAs having gas plenum filled with spring or another elements of design.

1. INTRODUCTION

Nowadays power reactor fuel assemblies (FAs) have reached a high level of manufacturing quality and operational reliability. On the whole, reactor cycles are completed without fuel rod failures [1]. However, especially in the first period there are some failures of fuel rods (up to about 0.01% of rod sum total [2]). This results in fission product releases into coolant system.

Fission gas products (FGP) partially escape through a cladding defect and water entering a fuel rod starts reacting with fission products. As a result volatile chemical compounds are formed that may escape like FGP or dissolve and leave a fuel rod as dissolved species.

The resulting high activity concentration in the primary coolant circuit is largely responsible for increased irradiation exposure of plant personnel. The larger portion of FGP from failed fuel rods reach the atmosphere and poison it. Radioactivity releases to the atmosphere cause irreparable harm to people and nature.

Since nuclear plants have licensing limits to volatile fission product releases to the environment the careful monitoring of clad failure evolution becomes indispensable. Limitation on the activity concentration level by the licensing limit results in a loss of reactor operational flexibility.

On account of this the nuclear fuel reliability receives the highest priority in the nuclear industry today. Fuel manufacturers have programs aimed at achieving defect-free fuel operation [2,3]. These programs cover as a rule fuel quality inspection at the fuel manufacture plant and detailed on-site examination of spent FAs.

In order to decrease radioactivity releases due to fuel failures, the reactor is shut down and failed FAs are transferred to a cooling pool. Thus a large amount of almost fresh fuel is removed from the power cycle which entails high economical losses.

The poolside inspection of irradiated FAs to identify failed rods (leakers) - is the main part of FA reconstitution technology. Another reason of leaker identifying necessity (but already inside spent FAs and including the subsequent certain removal of the detected leakers) - is to ensure the FA transmission feasibility for dry storage and for reprocessing.

Nowadays the main economical, technical and technological aspects of poolside fuel inspection and repair (reconstitution) of FAs have been resolved in countries having high level of economics and atomic energy [1,4,5,6]. The effectiveness of inspection and reconstitution efforts evidently depends primarily on leak-tightness test probe quality (sensitivity, accuracy and reliability).

Moreover the internal rod gas pressure - is one of the main critical parameters that forms rod mean life in the reactor core, therefore this parameter is always in field of sight of the researchers. According to the stated reasons the aim of our efforts during last dozen years became the elaboration of method and technical instruments for non-destructive leak-tightness detection and gas pressure measuring inside irradiated fuel rods (both individual and within FA) under poolside and hot cell conditions.

2. THERMOPHYSICAL METHOD

Nowadays different information sources describe great number of methods and devices used for leak-tightness and pressure tests of rods and FAs, see, for example [7-11] and others. However, almost all of them are far from being both completed and utilized in practice and are interesting for us only as an illustration of the free flight of a technical idea.

Among well-known technical decisions two methods find practical application, one of them is based on ultrasonic sensing of rod plenum for the presence of water in it [See 4, or French modification named «Echo-330»], and the other one - on analyzing the intensity of Kr-85 gamma spectrum in the plenum area [12].

Each of them has some advantages, but at the same time many disadvantages are inherent in them that limit their application. For example, the above gamma-spectrometry method of gas pressure measurement inside irradiated fuel rods is comparatively intricate to realize under poolside conditions, it has numerous disadvantages of different methods based on radioactivity parameter analysis, such as:

- Burn up dependence (low sensitivity after low burn up),
- Influence of external radioactive background (need for careful collimating),
- Influence of irradiated fuel storage time,
- Influence of uncertainty in initial helium filler pressure in fuel rods, etc.

This method cannot be used for identification of defective rods within irradiated FA because of Kr-85 gamma-activity influence exerted by adjacent fuel rods.

The above-mentioned method of ultrasonic sensing (or a similar one) is free from the enumerated disadvantages and proved well for failed rod detection in in-pool irradiated FA inspection. But some limitations are inherent in this method, e.g.:

- Sensitivity - not less than 0.5 gram of water inside plenum,
- Only bottom plenum siting; insensitivity to other types of rod defects (for example, low gas leaker),
- Insensitivity to internal rod gas pressure, etc.

This method is not applicable for rod inspection on its short-term storage because of water evaporation as a result of afterheat.

Meanwhile the obtained results and the experience that have been gained in the field of our experimental work allow to be firmly convinced that the thermophysical non-destructive test instrument application in this area of fuel inspection will give not only huge ecological and economical benefits but also unbiased important and interesting results.

The developed principle of gas pressure measurement is based on the well known thermophysical method of the parameter measuring of an object under study, described in [13,14], where to measure the liquid flow rate and to detect defects and cracks the use is made of the perturbation effect of a heat flux going from a heater and changes are recorded in the temperature difference as dependent on the object position in relation to the heater as a result of the effect of the searched for parameter of the object.

The applied thermophysical method resulting parameter to be measured is gas pressure inside a fuel rod. In essence the thermophysical principle which forms the basis of pressure measuring method consists in the fact that in a local area of a gas plenum of a fuel rod a fixed thermal perturbation of cladding takes place leading to natural convection and accompanying it thermodynamical processes in plenum gas volume. Heat exchange between gas, warm cladding and environment depends upon the kind of a gas, its physical properties and pressure. By recording the cladding temperature field in space and time one gets information on a parameter under measurement. The information is interpreted with the help of graduated characteristics taken from standard specimens - rod imitators, filled with the same gas, as the rod under study, but having parameters known at high accuracy in the range needed.

It is obvious that in the measurement process the temperature field contains information not only on the parameter being measured but also to a significant extent on such affecting factors as:

- Manufacturing scatter of cladding geometrical sizes,
- Scatter in thermophysical properties of cladding material,
- Unstable environmental parameters,
- Multicomponent gas composition,
- Oxide film and crud at cladding surface,
- Fuel and solid fission products available in a fuel rod, etc.

Our design of the probe, method of measurement and special mathematical method of data processing allow us to single out the information on a gas pressure at adequate accuracy.

The technical problems are typical and have been resolved using the known approaches. This comprises choice of materials and elements, automation of measurements, fabrication of standard specimens of pressure and gas composition, introduction of the developed measuring device into the process line (either research or technological), metrological certification.

During the technique development two options of irradiated rod gas pressure non-destructive measurement system have been realized, based on the above-mentioned method, that is caused by a natural course of the method development and distinction in particular conditions of its application. Meanwhile, our thermophysical non-destructive rod internal gas pressure measuring method is universal from the point of view of rod inspection realization place and applicable both for poolside and hot cell conditions. In other words, the method, used for hot cell conditions of rod inspection will be efficient in poolside rod inspection conditions and on the contrary, the method, used for poolside rod inspection conditions will be efficient in hot cell conditions.

3. ROD TOTAL GAS PRESSURE MEASURING DEVICE

The described thermoconvective principle of gas pressure measurement inside irradiated fuel rods was realized for the first time by device, structural scheme of which is shown in Fig. 1.

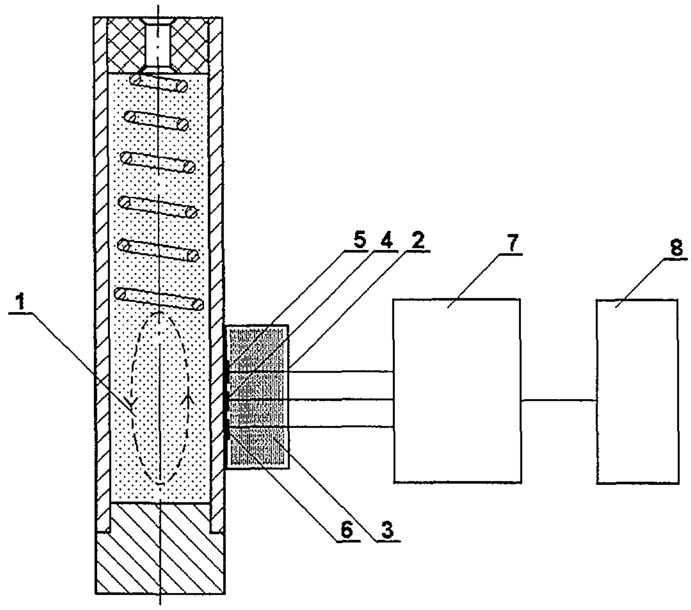

FIG. 1. Structural scheme of rod gas pressure measuring device.
1 - gas plenum; 2 - pressure probe; 3 - rubber bed; 4 - heater; 5,6 - thermoresistors;
7 - power and measurement block; 8 - personal computer.

Pressure probe 2 consists of a rubber bed 3 accommodating surface heater 4 and thermoresistors 5,6. Thermoresistors are connected to measuring bridge of block 7, that has controllable power source for measuring bridge, measuring amplifier, controllable power source for heater 4 and time interval setting mechanism. The automated control of the device blocks, the recording of measuring bridge unbalance voltage, that is proportional to a temperature drop in fuel rod cladding under study, as well as the computation of the searched for value of gas pressure are carried out with the help of personal computer 8.

The pressure probe is pressed on to a plenum of rod under study and the measurement process is carried out, recording the above-mentioned unbalance voltage during and after heat perturbation. The extreme value of the recorded curve has been taken as an informational parameter in the first experiments with irradiated rods. In the posterior experiments the special mathematical data processing and analyzing were applied to the recorded curve.

The experimental tests with variations in environmental temperature, cladding wall thickness and probe pressing conditions showed that using of this scheme the errors effected by those influencing parameters can be almost completely eliminated.

Thus, by thermoconvective gas flow excitation inside a leak-tight object through a short-term thermal perturbation of rod cladding and recording the cladding temperature drop in close proximity to the heated area it is feasible to measure gas pressure inside the object. It should be noted that this approach assumes that gas composition and content of the main gas mixture constituents are well known.

Feasibility of the developed method of total internal gas pressure measuring has been checked experimentally under BN-350 fast breeder reactor cooling pool conditions on a series of individual irradiated fuel rods. The so-called measuring manipulator (pressure probe with pressing mechanism) has been installed on the inspection stand. The inspection stand structural scheme and picture of applied measuring manipulator with hand remote control is shown in Figs 2 and 3.

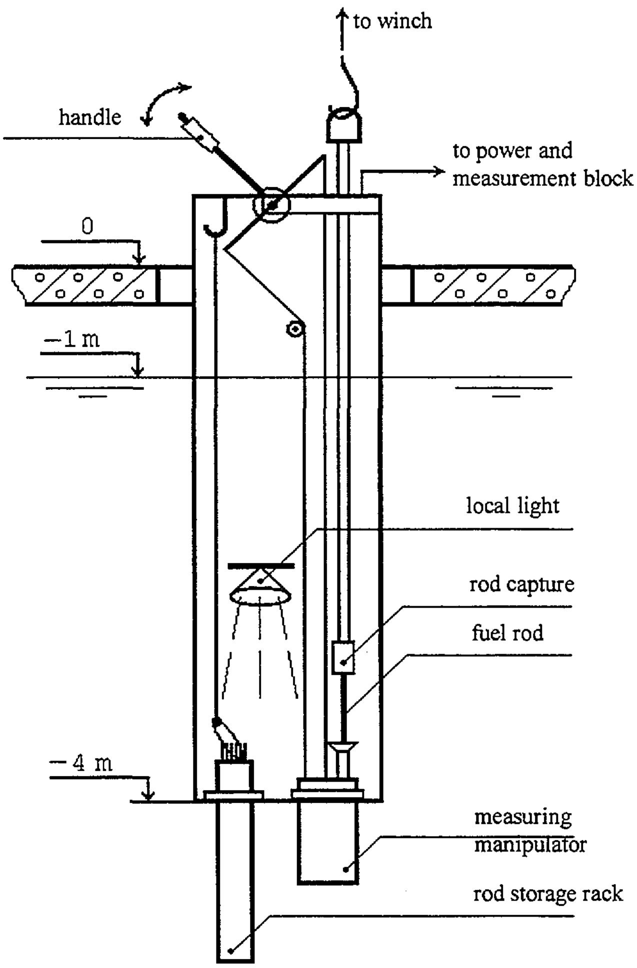

FIG. 2. Inspection stand structural scheme.

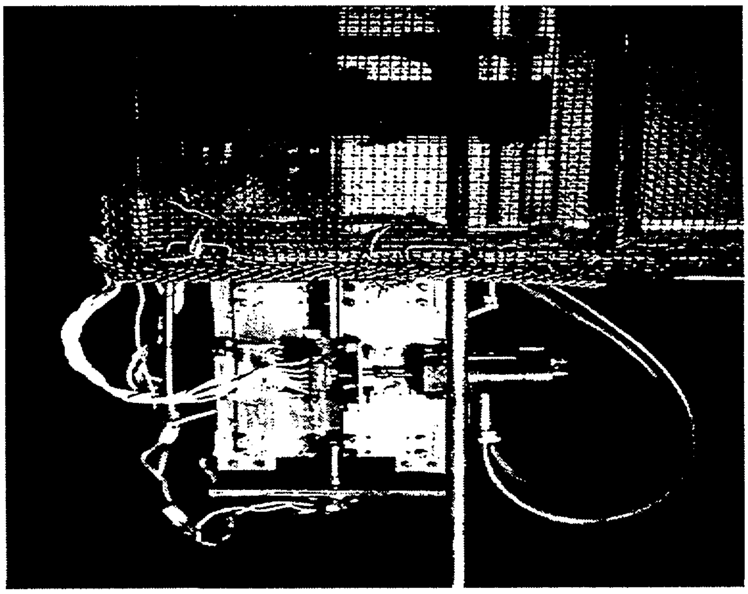

FIG. 3. In-pool rod gas pressure measuring manipulator.

A fuel rod with the bottom gas plenum was placed into the guiding funnels of the measuring manipulator that had two proximity sensors for fuel rod and its spacer wire orientation and positioning relative to the pressure probe. The first sensor is placed into lower guiding funnel and the other one - opposite to the pressure probe center. After the fuel rod and its spacer wire positioning an operator pressed the pressure probe on to the middle part of the rod gas plenum and the internal gas pressure measurement process started.

Fuel rod pressure measurements were accomplished using standard specimens filled with helium-xenon-krypton mixture with 7% of helium. The measured average results are in good agreement (at the accuracy up to 0.1 MPa) with the values calculated by the computer-calculating program for FGP releases from ceramic fuels as irradiated in BN-350 reactor. To experimental direct check the results of gas pressure was randomly measured by puncturing of several fuel rods placed under hot cell conditions. The comparison of the data received by destructive and developed non-destructive methods showed that there is full agreement of the results within the measurement error.

4. FUEL ROD INTERNAL GAS PARTIAL PRESSURE MEASURING SYSTEM

The presently used method and instruments have been improved, their technical potentialities have been widened, and the advantages of modern computer means of control and calculation of the experimental results have been applied. This assured the possibility of quantitative determination of the internal rod gas composition inside irradiated fuel rod and of improving the accuracy, efficiency and validity of the internal gas pressure measuring method. As a result, the unified system of non-destructive internal gas parameter inspection has been developed, it is designed for a leak-tightness test and measurement of total pressure and main gaseous constituent partial pressure inside irradiated power reactor fuel rods of any type existing in Russia.

The internal gas composition inside the cladding of the irradiated fuel rod is multicomponent, but we are talking about the inspection of a quasibinary gaseous mixture, that is quite enough for minimization of unstable gas composition influence on the method accuracy. We consider a model of a binary mixture consisting of two stable constituents: filler gas - helium and a gas that is formed under nuclear fuel operation - FGP. The parameters to be measured are partial pressure of helium and partial pressure of FGP.

It is apparent, that the internal gas composition inside irradiated power reactor fuel rods is not constant (i.e. relative gas constituent quantitative content in gaseous mixture of the particular rod is unequal to the relative content of the other particular rod) due to several reasons. For example, first, technological scatter in parameters of initial gas filling (sometimes up to 20%). Second, scatter in fuel properties and its operational conditions. And third, possibility of leakage (primarily helium) due to a cladding defect. In this connection the elaboration of a device to measure the gas pressure inside irradiated fuel rods that does not need the stable gas composition of rod under study was undoubtedly an urgent problem.

The physical principle and the main measuring scheme that are the basis of the developed system have been described above (See Fig.1). As distinct from them, the system is calibrated using standard specimens of pressure and composition, filled with mixture of helium, xenon and krypton with accurately known filling parameters (composition and pressure) in the needed range. As a result of the calibration the graduated relationships were derived in the form of calibration surfaces, which were used to compute the searched for internal partial gas pressures.

Nowadays the data processing procedure have been improved and carried out by special mathematical method with using of the preliminary classification of observations. In essence the data processing procedure consists in deriving of the graduated relationships of searched for the rod under study parameters as a function of some its generalized features. The generalized features are obtained from the a priori set of all rod measuring features by the special kind functional nonlinear optimization procedure application. The graduated relationships and generalized features are calculated with the help of training set application. The so-called training set is the feature vector observations of the standard specimens.

The developed system is a personal Intel-compatible computer base apparatus-program complex, hardware in the form of electronic blocks and devices, and a pneumatic measuring manipulator with pressure probe. All operations relevant to measurement and data processing are accomplished in automated mode. The measuring manipulator can be installed in a fuel inspection rig for poolside inspection or independently in a hot cell. The main technical characteristics of the measuring system are given in Table I.

The system is capable of operation under two modes. The first one is designed for express grading fuel rods into three groups: leakers, those having pressure close to design one and those having pressure significantly higher than the design one (time of measurement is 1 minute). The second mode is intended for quantitative measurement of helium and FGP partial pressures (time of measurement is 15 minutes). The availability of two modes makes the inspection process more flexible and efficient in terms of time used.

The system has been checked experimentally under hot cell conditions at Research Institute of Atomic Reactors in Dimitrovgrad [15] on a series of individual irradiated fuel rods. The results obtained and the experience gained point to the reliable and highly accurate operation of the system. The first results of non-destructive examination of actual fuel rods have been received in 1992 for standard spent WWER-1000 fuel rods and are given below in Tables 2 and 3. The fuel characteristics and operational conditions were as follows: 3-year cycle; 3.6% enrichment; burn-up of 34.7 MWd/kgU.

TABLE I. MAIN TECHNICAL CHARACTERISTICS OF THE PRESSURE MEASURING SYSTEM

Technical characteristics	Value
Range of pressure measurement, MPa	0.10-5.0
Range of helium pressure measurement, Mpa	0.10-3.0
Error of total and helium pressure measurement, Mpa	(0.15
Range of FGP pressure measurement, MPa	0.10-2.0
Error of FGP pressure measurement, Mpa	(0.10
Total time of single fuel rod measurement, min.	15
Time per single fuel rod in sorting, min.	1
Environment	water, air
Temperature of environment, (C	15 – 60

TABLE II. RESULTS OF WWER-1000 FUEL ROD INSPECTION

NN	Fuel rod No.	Date	Time	He pressure, MPa	FGP pressure, MPa
1	224	07.08.92	09:55:22	2.19	0.09
2	224	07.08.92	10:14:58	2.14	0.06
3	291	07.08.92	15:24:57	2.17	0.02
4	291	07.08.92	15:48:54	2.11	0.03
5	291	07.08.92	16:06:14	2.11	0.03
6	60	10.08.92	12:47:32	2.17	0.01
7	60	10.08.92	13:03:52	2.18	0.02
8	60	10.08.92	13:21:51	2.25	0.01
9	161	10.08.92	14:01:27	2.30	0.00
10	161	10.08.92	14:22:37	2.31	0.02
11	159	10.08.92	14:46:40	2.45	0.07
12	159	10.08.92	15:12:53	2.43	0.05
13	104	10.08.92	15:59:19	2.38	0.10
14	138	10.08.92	16:21:28	2.15	0.06
15	138	10.08.92	17:21:26	2.20	0.06
16	192	11.08.92	10:46:14	2.20	0.02
17	192	11.08.92	11:03:17	2.10	0.03
18	157	11.08.92	11:25:24	2.41	0.01
19	157	11.08.92	11:44:09	2.42	0.02
20	157	11.08.92	12:05:59	2.50	0.01
21	34	11.08.92	12:38:18	2.45	0.08
22	224	12.08.92	09:21:41	2.26	0.04
23	224	12.08.92	09:43:08	2.18	0.05
24	224	12.08.92	10:02:12	2.19	0.05
25	224	12.08.92	10:30:26	2.19	0.04
26	224	12.08.92	10:47:12	2.24	0.04
27	224	12.08.92	11:37:22	2.22	0.04
28	224	12.08.92	12:52:21	2.29	0.04
29	224	12.08.92	13:07:40	2.24	0.11
30	104	12.08.92	13:32:04	2.24	0.06
31	104	12.08.92	13:48:17	2.31	0.07
32	104	12.08.92	14:10:06	2.31	0.04
33	104	12.08.92	14:28:16	2.29	0.08
34	104	12.08.92	14:43:44	2.29	0.04

TABLE III. RESULTS OF ROD RANDOM PUNCTURE TEST

Fuel rod No.	224	104
Free volume, cm^3	28.08	27.73
Pressure, MPa	2.396(2.27)[a]	2.400(2.37)[a]
He, %	97.81	97.88
N_2, %	0.11	0.09
O_2, %	0.02	0.02
Kr, %	0.22	0.22
Xe, %	1.84	1.78

[a] Middle value of NDT test

The comparison analysis of the above results of the random rod pressure measurement by puncture and developed non-destructive method with the help of the pressure measuring system shows their absolute agreement within the measurement error.

Further improvement of the thermophysical method and technical instruments has resulted in the measuring system variant development for leak-tightness test and internal gas partial pressure measuring of peripheral rods in RBMK type FA. The picture of the given system measuring manipulator is shown in Fig. 4.

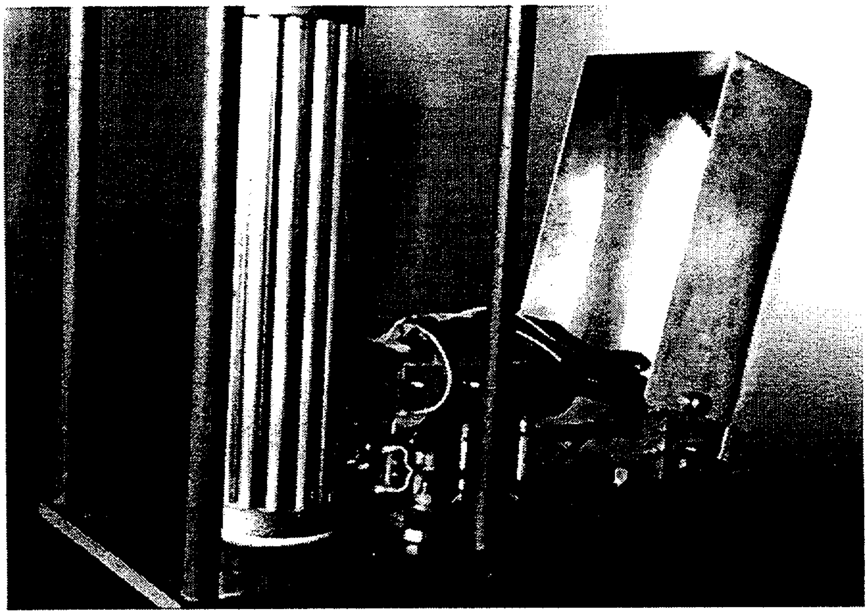

FIG. 4. Measuring manipulator for FA inspection.

5. CONCLUSION

A positive experience in development and operation of thermophysical instruments for NDT of internal gas pressure of Russian NPP rods in poolside and hot cell conditions [15] as well as in fuel production manufacturing conditions [16] have been gained to the present time. Many problems relevant to reliability, maintainability and convenience in operation for the equipment have been resolved. As a result the following advantages of the thermophysical method are revealed:

Extended range of its practical application, since neither rod afterheat level, nor rod plenum siting (top or bottom) influence on the quality of test results and the inspection of both single rods and FAs (peripheral rod line) is feasible

Universality in terms of rod inspection realization place (applicability both for poolside and hot cell conditions)

Extended information volume, since the information quality is comparable to the obtained only by rod puncture test (partial pressures of main gas constituents and gas mixture total pressure, rod leakage and tightness)

Reliable and authentic detection feasibility of every defective rod (rod with any probable defect type) because of realization of one (or more) of the following criteria under investigation:

- Low helium partial pressure (or its complete absence) in rod internal gas mixture,
- Abnormal low (or high) rod total internal gas pressure,
- Presence of water or steam inside rod.

Today the work is under way in the following directions:

- Improvement of features of the equipment now in action,
- Improvement of the method and technical instruments to inspect other fuel rod types (PWR type and others),
- Defective rod detection system development to inspect FA internal rod lines (without FA dismantling).

As to the third direction realization level, which among listed undoubtedly has the greatest potential practical importance and potentially the most beneficial, it should be noted, that we have already proved experimentally in laboratory poolside conditions the feasibility of the given development for Russian NPPs with the help of 1.5 mm thickness pressure probe variant and Russian type FA mock-up. By other words, the practical realizability of the given development does not cause any doubts for us.

The analysis of state of the art and the presented practical results of our work in the given area of science and engineering gives good prospects and the right to approve the expediency of wide application and further improvement of thermophysical method and technical instruments for inspection of standard, experimental as well as refabricated fuel rods and FAs in both poolside and hot cell conditions with a view to reconstruct defective FAs or investigate the individual rods during the realization of the program relevant to fuel perfection, increase of rod mean life and reliability of operation inside reactor core.

The described thermophysical method and technique have been experimentally checked during the examination of all types power reactor fuel rods existing in Russia (WWER, RBMK, BN) and undoubtedly could form the basis for new technique development for non-destructive examination of PWR (and other) type rods and FAs having gas plenum filled with spring or another elements of design.

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