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**MICROWAVE MEASUREMENT
OF HIGH TEMPERATURES
WITHIN NUCLEAR REACTORS
INTERIM REPORT**

T. R. BILLETER AND D. P. BROWN

OCTOBER, 1967

**AEC RESEARCH &
DEVELOPMENT REPORT**

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T. R. Billeter and D. P. Brown

Instrumentation Section
Applied Physics and Electronics Department

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Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U.S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

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MICROWAVE MEASUREMENT OF HIGH TEMPERATURES WITHIN NUCLEAR REACTORS INTERIM REPORT

T. R. Billeter and D. P. Brown

INTRODUCTION

Accurate and precise measurements of nuclear reactor in-core temperatures are required to achieve operational safety and optimum performance. For a particular reactor design, temperature of constituent materials is one factor limiting the maximum operating power level. Temperatures of fuel elements, coolant, moderator, and other reactor components must be monitored to assure that the various components and materials are maintained within appropriate design temperature ranges. For example, fuel elements must be operated below their phase change temperature; control of coolant temperature subsequent to measurement reduces the danger of excessive fuel cladding erosion; and thermal stresses within other reactor components may be ascertained by measuring the temperature of the various components. In general, measurement of temperatures is necessary to assure that materials are not thermally stressed beyond their limits. In addition to undesired consequences of a reactor shutdown caused by material failure (e.g., at excessive temperature), safety hazards are engendered by operation of materials above safe design limits.

The purpose of this work, the initial results of which are reported, is development of temperature sensors that will operate reliably for long periods of time within a nuclear reactor. The sensor range of temperature operation, sensitivity, speed of response, accuracy, and repeatability of indication for multiple heating cycles to maximum temperature are being investigated. Operational effects upon the temperature sensor using metals other than those usually employed at microwave frequencies will be assessed during the development work.

Of the two microwave sensors described in this report, one relates the temperature-induced frequency shift of a microwave cavity to the temperature of the component being monitored. The other system, operating passively, uses a microwave radio-meter to measure the temperature-related electromagnetic energy emitted from the component monitored or from a black body in close proximity.

Experimental work described in this interim report concerns the active measurement system only. The theory of the passive microwave measurement method is discussed briefly. This work is sponsored by the United States Atomic Energy Commission, Division of Reactor Development and Technology.

SUMMARY

Two microwave methods of measuring nuclear reactor in-core temperatures are proposed. Measurements by the first of the two methods being investigated, the active system, are accomplished by relating the frequency shift of a microwave cavity to the temperature of its surroundings. In experimental tests, the measurement sensitivity of this method proved to be 300 kHz/°C for temperatures to 1000 °C. Because the measurement of frequency to an accuracy of one part in 10^6 is possible with ease, a theoretical precision of measuring temperature is ± 0.05 °C. This is adequate to satisfy temperature sensor criteria of many recently constructed reactors. Response of the temperature sensor was not determined during the initial experiments; however, the sensor accurately monitored a rate-of-increase of temperature of 30 °C/min. Stability of the required instrumentation proved excellent, and repeatability of measurements was only slightly affected by oxidation of the copper waveguide at the elevated temperature of 1000 °C.

Experimental work with the second method, a passive measurement system, requires employment of a microwave radiometer. Theoretical temperature sensitivity of the instrumentation indicates that a 1 °C change at the sensor will provide a 0.45 °C temperature change at the radiometer. Both temperature measurement methods require a waveguide to be inserted within a high-temperature and possibly corrosive environment. Methods which would retard the damaging effects of an oxidizing atmosphere are suggested in this report. Although preliminary in nature, experimental results indicate that microwave methods of monitoring nuclear reactor in-core temperatures during normal operation are adequately sensitive, and should materially reduce problems associated with other types of temperature sensors.

BACKGROUND

To effectively measure reactor in-core temperatures, certain criteria, which must be satisfied by the temperature sensing system, are dictated by the dynamic operating temperatures for which the sensors are designed. The criteria for the temperature sensors described in this interim report are based on requirements for advanced reactor facilities. These include gas cooled, graphite moderated reactors such as UHTREX, and both liquid metal and steam cooled reactors. For two specific reactor types, general component operating temperatures and other pertinent data are given in Table I.

Reference to specifications of these reactors indicates that temperature sensors should be capable of operation between 50 °C and 1500 °C to provide proper monitoring of coolant and/or moderator temperatures. Because the fuel elements can be quite small, temperature sensor size is restricted if it is to be attached to the fuel element.

TABLE I. *Illustrative Reactor Operating Characteristics*

UHTREX

Fuel Elements	Graphite cylinders, 1 in. OD, 0.5 in. ID, 5.5 in. long. UC ₂ particles dispersed in graphite.
Moderator	Vertical graphite cylinder, 39 in. high, 70 in. OD, 23 in. ID.
Fuel Channels	312 radial, horizontal holes; four fuel elements/channel.
Coolant	Helium @ 500 psia Max.; 870 °C Max. inlet, and 1320 °C Max. outlet.
Fuel Temperature	1845 °C Max.; 1483 °C average.

EBR-II

Fuel Elements	Pin type, sodium bonded enriched uranium, 0.144 in. OD, 14.22 in. long.
Coolant	Sodium, 371 °C inlet, 473 °C outlet.
Fuel Temperature	Maximum cladding surface temperature 570 °C; maximum fuel center temperature 689 °C.

Fuel element temperature measurements from 100 °C to 1600 °C should suffice for normal reactor operation. Temperature sensors described in this report are neither intended to respond nor capable of responding to the very high transient temperatures that might occur during very abnormal power pulses. In contrast to the response time required to measure such abnormal transients (of the order of milliseconds), the microwave sensors being developed are intended to react to temperature variations with periods of the order of 20-30 seconds. Outlet coolant temperature must necessarily be measured with greater accuracy than the difference in temperature values for normal and "scram" initiating operation. Provision of accurate monitors for individual channels can contribute substantially to the maximum performance of large gas cooled

reactors. For such reactors, the required accuracy for temperature monitors is approximately 8 to 10 °C at an operating temperature of 540 °C.⁽¹⁾ Consequently, temperature sensor development of the microwave type will be concentrated on methods capable of yielding an accuracy of approximately ±5 °C. The dynamic temperature environment within a reactor requires that appropriate sensors respond for many temperature cycles without adverse effects upon their life, accuracy, or sensitivity.

Other possible methods of measuring reactor in-core temperature include thermocouples, resistance-temperature detectors, and thermistors. The major problems associated with these detectors in a radiation environment are errors caused by radiation heating, degradation of insulation, transmutation of constituent materials, lattice defects which result from elastic neutron collisions, and the thermal conductivity of lead-in wires. Errors as high as 815 °C at a true temperature of 2490 °C are reported⁽²⁾ for thermocouples. Resistance-temperature probes are moderately damaged at fast neutron fluences of 10^{17} n cm⁻² and gamma exposure of 10^{10} ergs g⁻¹(C), whereas most thermistors perform satisfactorily only to a neutron fluence of 10^{15} n cm⁻² (E > 2.9 MeV) and gamma exposure to 10^{10} ergs g⁻¹(C).^(3,4) Prolonged use of thermocouples in reactors for neutron fluences to 10^{22} n cm⁻² has indicated the major problem is due to composition change;⁽²⁾ however, in addition to composition change due to transmutation, an additional error is introduced by metal phase separation for W/W-25% Re thermocouples.⁽⁵⁾ Solution of the problems associated directly with the sensor does not eliminate problems associated with lead-in wire insulation. Organic insulations exhibit almost complete failure when exposed to gamma radiation of 2.8×10^{10} ergs g⁻¹ (C).⁽⁶⁾ The metal oxide and ceramic insulations lose varying amounts of their insulative properties depending upon radiation level, temperature, and time-at-temperature.⁽⁷⁾

In this report, two developmental microwave methods of temperature sensing are described which we anticipate should provide the accuracy and longevity desired for nuclear reactor application. These microwave sensors should also circumvent certain problems associated with previously mentioned temperature sensors. Most notable, the microwave sensor uses a hollow metallic pipe to transmit temperature-related signals from the reactor interior to external electronic equipment, thereby essentially negating problems associated with lead-in insulation. Because the expansion characteristic of the metal sensor is the property upon which the operation of one microwave method is based, relatively minor changes in its performance are expected for operation in a radiation field. The microwave sensor and transmission line, made entirely of metal, should provide measurements to 1000 °C using presently fabricated microwave waveguide. Higher temperature capability will require microwave components made of higher melting point metals, such as the nickel-chromium steel suggested in this report.

DISCUSSION

TEMPERATURE MONITORING BY FREQUENCY SHIFT METHOD

The resonant frequency of a microwave cavity is determined by physical size, geometry, and by the mode or distribution of electromagnetic fields within the cavity. By selecting an appropriate cylindrical cavity and operating it in the TM_{010} mode*, the resonant frequency, f_o , of the cavity is related to the radius, a , of the cylinder by⁽⁸⁾

$$f_o = \frac{c}{2.61a}$$

where c is the velocity of light. The size of the cavity, fabricated of metal, will depend upon its operating temperature.

* In the TM_{010} mode, the magnetic field is transverse to the propagation direction (axis of the cylindrical cavity) and the subscript, 010, denotes the number of variations of the magnetic field in the circumferential, radial, and axial directions, respectively.

For a metal, the change in dimension may be expressed by⁽⁹⁾

$$L = L_0 (1 + \alpha T + \beta T^2 + \gamma T^3 + \dots).$$

The values of α , β , and γ are determined empirically and are usually functions of temperature. However, for some metals the values remain nearly constant over the range of temperatures expected in these investigations. As an approximation, the terms βT^2 and those with a higher order of T may be neglected when compared with αT . For maximum variation of dimension with temperature, a metal with a maximum value for α can be selected. For a linear frequency shift with temperature, a metal with a constant value of α over the temperature range of interest ($\sim 100^\circ\text{C}$ to 1000°C) should be selected.

The metal selected for initial experimental tests was a high expansion, nickel-chromium steel*. Only the cavity is fabricated from this metal; the remainder of the waveguide is of OFHC copper, which has a coefficient of thermal expansion nearly the same, but not as linear, as the stated steel alloy. A graphical sketch and a picture of the experimental microwave sensor illustrating its simplicity are given in Figures 1 and 2. To provide the required high temperature capability, both the metal cavity and input waveguide were brazed in a hydrogen atmosphere, using high melting point alloys.

Prevention of internal oxidation of components at elevated temperatures was accomplished during experiments by evacuating the metal waveguide and cavity. Although the external metal was badly oxidized by extended exposure to the high temperatures, no adverse effect occurred in the measurement accuracy or stability for the exposure period. However,

* Carpenter Steel Company Type 22-3 containing 22% nickel, 3% chromium, and the remainder iron.

Waveguide - Coupling Part

"22 - 3" Cavity

Complete Assembly

Neg PNL 0670553-12

FIGURE 1. *Parts and Complete Assembly
of Microwave Temperature Monitor*

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FIGURE 2. Photograph of Experimental Microwave Temperature Sensor Unassembled Parts and Final Assembly Shown

the corrosion problem (including oxidation) will be alleviated in proposed designs by a protective coating or by physical placement, in a vacuum enclosure, of a material of high heat conductivity between the enclosure and the cavity.

An oscilloscope record of the microwave cavity response, shown in Figure 3, illustrates the ease with which the high "Q" resonance may be monitored. The base line represents 100% power absorption; thus, it is apparent that nearly 100% coupling of the microwave signal to the cavity, at its resonant frequency of approximately 15 GHz, has been attained.

During a laboratory experiment, the heated portion of the waveguide was evacuated to forepump pressures (approximately 2×10^{-2} mm Hg), and the cavity resonant frequency was monitored with a manually adjusted microwave frequency meter. The experimental equipment block diagram, Figure 4, shows the basic elements required in the measuring instrumentation. Automatic readout of the temperature was easily accomplished with the equipment shown in Figure 5. The cavity resonant frequency, as monitored by a minimum of the detector signal, was directed to a lock-in amplifier. A voltage proportional to the shift of the test cavity from a reference value, enables proper temperature monitoring and provides the signal required to shift the driving oscillator frequency.

EXPERIMENTAL RESULTS FOR THE FREQUENCY SHIFT METHOD

Experiments conducted with two cavity-waveguide assemblies essentially confirmed the theoretical calculations. One assembly was tested only to 700 °C because of the lower temperature brazing material used, whereas the second assembly, brazed with a higher melting point alloy*, was subjected to 1000 °C during

* "Nicoro," Western Gold and Platinum Company

Neg PNL 0670553-6

FIGURE 3. *Oscilloscope Response of Microwave Cavity Resonance. Horizontal Scale: 300 MHz/cm; Vertical Scale: Relative Signal from Detector*

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FIGURE 4. Experimental Equipment Schematic for Shift-of-Frequency Temperature Measurement

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FIGURE 5. *Experimental Equipment for Automatic Readout of Shift-of-Frequency Temperature Measurement*

its test. Each temperature monitor exhibited a nearly linear response of resonant frequency versus temperature. One demonstrated a sensitivity of 290 kHz/°C; the other 310 kHz/°C. The slightly lower than predicted sensitivity may be attributed to the use of sensors not made entirely of the 22-3 metal. The common wall between waveguide and cavity is copper. Verification of the ultimate sensitivity possible, must await further experimental tests in which the cavity waveguide assemblies are made completely of 22-3 steel alloy.

During tests with the most sensitive cavity, the feedback voltage of the lock-in amplifier was also recorded, and the results of these data and the frequency-shift data are shown in Figure 6. Again, the linearity of response is quite evident. Data recorded during increasing or decreasing temperature cycles were nearly repeatable, with only small, but constant, differences being noted. These minor inconsistencies were apparently due to the slight oxidation of the cavity inner wall, lowering the resonant frequency by several MHz. By evacuating the remaining trace oxygen from the system, this problem would be circumvented.

Response of the sensor to step increases of temperature has not been investigated to an extent adequate to include data in this report. However, time response should be related directly to the mass of the cavity sensor and to the thermal conductivity of the metal from which it is fabricated. During the conducted experiments, temperature rate-of-increase was no greater than 30 °C/min, at which value the data are consistent with those obtained at reduced heating rates. Because of the sharp cavity resonance ($Q \approx 1000$), no difficulty was experienced in locating or tracking the response either by automatic readout equipment or by the manually adjusted wavemeter. As evidenced by the response characteristic of Figure 3, the cavity absorbs

Neg PNL 0670553-3

Cavity Temperature (°C)

FIGURE 6. Output Response of Microwave Temperature Monitor

nearly 100% of the incident power at the resonant frequency. Thus, ease of monitoring is ensured even though the power reflected by the cavity at frequencies other than the resonance frequency is quite variable. Cavity resonance would be even more prominent in such a display if the power output of the driving oscillator (Figure 3) were leveled to a constant value.

In performed experiments, oxidation of external surfaces of the input waveguide and cavity occurred at elevated temperatures, and would eventually cause loss of vacuum integrity of the sensor if the assembly remained in a high-temperature oxidizing atmosphere. Development of a truly long-lived in-core temperature sensor is dependent upon solution of the external corrosion problem. A partial solution would be the coating of the sensor assembly with an oxidation-resistant material,⁽¹⁰⁾ (e.g., desilicized molybdenum) or use of a material which forms a protective oxidation layer that impedes further oxidation of the underlying metal. Encapsulation of the sensor and waveguide in a vacuum-tight, corrosion-resistant metal, such as tantalum or molybdenum, would significantly extend the operating lifetime of the temperature monitors. However, there would be a delayed response to rapid temperature variations, and this would remain true even though the space between sensor and encapsulation were compacted with, for example, beryllium oxide.

TEMPERATURE MONITORING BY A RADIOMETRIC METHOD

At temperatures above absolute zero, all objects emit electromagnetic energy due to atomic and molecular activity within their structures. As the temperature of a body rises, the total radiation emitted increases, and the frequency at which the peak of radiation occurs is shifted upward. Although the energy radiated at microwave frequencies is small, a very

sensitive receiver (radiometer) with a wide r-f bandwidth will measure the energy as a function of body temperature. This method can thus provide the measurement of in-reactor body temperatures.

According to Planck's Law, a black body (one which does not reflect incident energy) radiates energy as a function of temperature, T , and frequency, f , according to the relation⁽¹¹⁾

$$E(f) = \frac{2\pi hf^3}{c^2 \left[\exp\left(\frac{hf}{kT}\right) - 1 \right]}$$

where k is Boltzmann's constant and h is Planck's constant. At microwave frequencies and for operating reactor temperatures, the term $hf \ll kT$; thus, the exponential is closely approximated by

$$\exp\left(\frac{hf}{kT}\right) \approx 1 + \left(\frac{hf}{kT}\right) + \frac{\left(\frac{hf}{kT}\right)^2}{2!} + \dots \quad (hf \ll kT).$$

With this substitution, the radiated energy is given accurately by

$$E(f) = \frac{2\pi kTf^2}{c^2}.$$

For an antenna, the average gain has an inverse square dependence on frequency; therefore, the total power received at the radiometer is independent of frequency, being proportional to kTB , where k and T have been defined, and B is the r-f bandwidth of the radiometer.

Most materials are not black bodies at microwave frequencies; thus, only their apparent temperatures are detected by the radiometer. The apparent temperature is the temperature that a black body must have in order to radiate the same amount of energy as the actual body. In electrical engineering parlance, the better the impedance match between the

radiating body and the receiver input, the more nearly the radiating body appears black.

For measurements of temperature within the reactor, the source of radiated microwave energy is a matched load at the end of the receiving transmission line. The temperature at the input to the radiometer will be due to energy radiating from the input waveguide walls, as well as to that from the matched load. For example, if we assume that the matched load (and reactor interior) is at 1000 °C, and the input waveguide has an average thermometric temperature of 513 °C, then the apparent temperature at the radiometer input is given by

$$T_r = \frac{T_t}{\alpha_n} + T_n \left(1 - \frac{1}{\alpha_n} \right)$$

where α_n is the attenuation, as a power ratio, of the input waveguide, and where T_r , T_t , and T_n are respectively the radiometer, termination, and waveguide apparent temperatures in °K. Because the termination is assumed to be matched to the input waveguide, its thermometric and apparent temperatures are the same, whereas the waveguide has a very low emissivity of 0.03. Therefore, its apparent temperature is -249.4 °C. For an input waveguide 20 ft long, α_n is 3.5 dB (power factor of 2.24) and the resulting apparent temperature as seen at the radiometer input is

$$T_r = \frac{1,273}{2.24} + 23.6 \left(1 - \frac{1}{2.24} \right) = 583 \text{ °K or } 310 \text{ °C.}$$

Actual thermometric temperature of the matched load could be monitored by introducing a compensating signal at the final stages of the radiometer. An assembled radiometer is illustrated in Figure 7. Input waveguide, to which the matched load sensor is attached, extends from the rear of the r-f electronics chassis.

Neg PNL 0672230-3

FIGURE 7. *Microwave Radiometer Used for Temperature Measurements*

CONCLUSIONS

Two methods using microwaves to measure in-reactor temperature indicate that both are appropriately sensitive and could be used to provide long-lived in-core temperature measurements. Laboratory experiments with the shift-of-frequency method demonstrated a sensitivity of 310 kHz/°C, with a nearly linear response over the temperature range of 30 °C to 1000 °C. A common problem with both techniques is the corrosion of sensors and input waveguide at elevated temperatures. Partial solution of this problem can be provided by evacuating the sensor and waveguide. Further work must be done to establish protective measures for the exterior of the metal components.

It should be possible to simultaneously monitor the temperature at many laterally separated points along the input waveguide. Equipment requirements are similar to those used in the performed experimental work, except the input waveguide must have microwave cavities that are resonant at slightly different frequencies and are located at each position for which temperature monitoring is desired. An automatic readout from the multiposition temperature monitor would be possible.

FUTURE PLANS

Experimental tests similar to those performed for the shift-of-frequency temperature monitor will be initiated with the microwave radiometer. A suitable high temperature matched load will be designed. Appropriate transmission waveguide which contributes a minimum signal emission must be obtained. Satisfaction of this requirement will assure that most of the received signal is emitted from the black body at the temperature of the reactor component being monitored. Accordingly, the waveguide should have a low emissivity of constant value over the temperature range measured.

Both microwave methods of measuring temperature require waveguide between the sensor and external electronic equipment. Metals from which commercially available waveguide is fabricated melt at approximately 1000 °C. To extend microwave techniques to higher temperatures, low-loss waveguide of appropriate metals must be fabricated. Because many metals are extruded in the form of cylindrical tubes, sensors compatible with propagating modes within cylindrical transmission lines will be investigated.

For maximum tolerance of the metal transmission waveguide to a high-temperature, oxidizing environment, methods that impede the oxidation rate will be investigated. To this end, and for increased sensitivity, a temperature sensor assembly totally of nickel-iron metal will be fabricated and tested for the shift-of-frequency method. It is also expected that the sensor/waveguide will be tested in a high-temperature sodium loop, assuming that metals suitable for microwave sensor/waveguide fabrication and useable in sodium are available.

Further experimental refinements will be incorporated into the automatic readout of temperature measurement systems. Planned experiments include conditions during which the various temperature sensors are subjected to high temperature for long periods of time, and for which automatic recording of output is provided.

Because the intended application of the developed sensor is within an operating reactor, efforts will be directed toward confirmation of laboratory data by testing an appropriate sensor in an advanced experimental reactor. UHTREX would provide the desired environment of high in-reactor temperatures. Measurement of fuel element temperatures within UHTREX might be effectively accomplished because of the size and shape of the element, and the fact that they are unclad. Experimental tests of the microwave sensors is anticipated in this or other advanced reactors.

ACKNOWLEDGEMENTS

The authors wish to acknowledge contributions of J. T. Russell in his early suggestions on the measurement of reactor in-core temperature by detection of internally generated microwave noise, and on the use of in-core resonant cavities for measurement of reactor operating parameters.

Comments and suggestions provided by W. L. Bunch are gratefully acknowledged, and the authors also thank Dr. P. O. Berrett* and L. D. Philipp for their investigative contributions during portions of the experimental effort.

* *Presently Professor of Electrical Engineering at Brigham Young University, Provo, Utah.*

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