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DESIGN FEATURES OF CAPSULES FOR
HIGH-TEMPERATURE IRRADIATIONS

by

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An analysis was made of the problems of control and measurement of specimen temperature and heat generation in a NaK-filled capsule containing a fuel specimen. A specific problem is used in this report to demonstrate the large uncertainties normally encountered even in capsules containing thermocouples. This analysis indicates that an improvement by a factor of more than three (i.e., from an uncertainty of $\pm 70^\circ\text{F}$ to $\pm 20^\circ\text{F}$ in the example used) may be obtained by use of a differential-thermocouple heat-flow meter and by use of a precision thermocouple-placement clip.

Since the irradiation damage suffered by fuel specimens is sensitive to small changes in temperature and burnup, improvements in precision in irradiation testing are of great importance in fuel studies. If the indicated improvement of precision by a factor of three is actually obtained when capsules of this design are irradiated, the experimenter will be able to draw much more reliable conclusions from a given testing program

INTRODUCTION

Irradiation of nuclear fuel materials at high temperatures and to high burnups requires precise control of experimental conditions under difficult circumstances.⁽¹⁾ The ambient temperature of most of the reactor space available for irradiation of experimental specimens is low compared with that desired for most experiments. The experimental materials must therefore be encapsulated and a heat barrier provided between the specimen and the ambient reactor surroundings. Widely diversified experience at Battelle over the last several years has served as the background for capsule designs that are believed to offer improved precision in testing. These capsules are primarily for irradiations in pool- or tank-type test reactors.

Specialized design problems are encountered in the usual case of fueled specimens that are desired to be irradiated at a preassigned elevated temperature in a neutron-flux field which is not accurately known and in a capsule whose heat-transfer properties are not accurately known. If internal instrumentation is not used, then the potentially large error of prediction cannot be corrected. Therefore, an instrumented capsule is required for precise experimentation.

The design of a capsule for precise testing must provide means to measure the specimen heat-generation rate and means to measure and control the specimen temperature.^(1,2) Measurement of the rate of heat generation is required to calculate the rate of burnup and to calculate the temperature at points where thermocouples cannot be placed. The temperature is measured as close to the specimen as possible because the errors in extrapolation are thereby reduced, but in many practical cases these errors are still large compared with the desired precision.

⁽¹⁾ References at end.

With these principles in mind, a design study was made to define the major regions of uncertainty and to devise practical schemes for improving the precision of measurement and control of specimen temperature.

FACTORS AFFECTING HEAT PRODUCTION

When a capsule containing fuel-material specimens is irradiated in a reactor, heat is generated inside the capsule primarily by fission recoils, with a small additional amount from gamma heating. Gamma-ray-heating measurements are almost a necessity since the calculation of this heating effect is quite involved. However, it is usually not necessary to repeat the gamma-ray-heating experiments for various capsule designs because the gamma heating is generally small compared with the fission heating.

On the other hand, the thermal-neutron flux in the specimen will generally change if the capsule design is altered. Although experiments can be performed to measure these flux changes, it would obviously be preferable if a simple calculational method could be used to estimate the effect of a given capsule design and fuel specimen upon the thermal-neutron flux. A semiempirical method developed by Lewis is widely used at the MTR.⁽³⁾ Errors in estimating the flux-depression factor in some cases may be as high as ± 20 per cent.*

Another factor to be considered in the design of an irradiation capsule is the variation of the flux during the irradiation period. These variations result from the changes in the reactor and capsule systems during this period. For example, control-rod positions will vary, the fuel distribution will change, and the other reactor experiments will have a variable effect. The variations due to these causes may be as large as +100 or -50 per cent, particularly if powerful absorbers are inserted in or withdrawn from neighboring positions. In the best cases, when all due care is taken in planning the experiment and no unexpected outside interferences occur, the estimated two-sigma limit for the uncertainty in the effective flux is about ± 20 per cent. For this reason alone, it is desirable to have a source of heat in the capsule which can be varied independently of the reactor operation. This then allows the total capsule heating to be adjusted to a rate necessary to maintain the desired specimen temperature regardless of the uncontrollable variations which occur.

The errors in estimating the fission heating can be compensated by the externally controlled heat. However, it is still necessary to keep the estimate of the fission heat fairly accurate to obtain an efficient capsule design. If the error in the estimate is too large, it will not be possible to insert a large enough electrical heater to cover the possible variations.

*All limits quoted in this report are engineering estimates of two-sigma limits considering realistic fabrication tolerances, thermal conductivity measurements and instrumentation precision. In most instances, data are not available for a statistical determination of these limits.

FACTORS AFFECTING HEAT TRANSFER

With auxiliary heat available, the amount of total heat that is dissipated to the final sink is controllable. The design of the capsule must be such that the total heat dissipation required to achieve the desired temperature

- (1) Must exceed the maximum nuclear heat (combined fission and gamma heat), thus precluding the possibility of having the specimen too hot with the auxiliary heater turned off
- (2) Must be less than the sum of the minimum nuclear heat and the maximum auxiliary heat, thus precluding the possibility of having the specimen too cold with the auxiliary heater in full use.

Capsule Size

Design of irradiation capsules would be simplified if there were no restrictions on the radial dimensions of the capsule. This would make it possible to control resistance to heat flow from the fuel specimen outward merely by making suitable changes in the length of the heat-flow path. However, capsule size must fit reactor test-cell dimensions, which are generally small, particularly in high-flux regions. Other considerations which lead to a size limitation include poison effects, reactivity-depression effects stemming from absence of moderator, restricted flow of cooling water, and high cost of reactor space. In the Battelle Research Reactor the test cells within the core are spaces created by the removal of 3 by 3-in. fuel-element sub-assemblies. The recommended maximum capsule diameter at this site is about 2-1/4 in. In the popular A-piece (in the beryllium moderator) facilities at the Materials Testing Reactor, 1-1/8-in. -OD capsules are preferred. The highest flux positions for capsules in the ETR require a 1-in. -OD limit.

The upper limit in capsule size dictated by the factors mentioned above, along with a lower size limit governed by fabrication and heat-removal considerations, leaves little leeway to utilize size as a design parameter.

Heat-Flow Barriers

The restricted capsule diameter makes it necessary to select various heat-flow barriers to create a large controlled gradient between the specimens and the outer capsule surface. A double-walled capsule configuration offers considerable flexibility in this selection, inasmuch as a variety of resistances to heat flow can be located in the annular space between the inner crucible and the outer shell. The wide range of heat-dissipation rates obtainable by this means, using the same basic capsule design (the same as that used later for a reference design), is illustrated by Figure 1. The heat-flow-rate values were derived from expressions for two-dimensional heat flow, since the small axial heat losses expected from such a capsule do not influence the comparisons.

FIGURE 1. THE EFFECT ON HEAT-DISSIPATION CAPACITY OF VARIOUS HEAT-FLOW BARRIERS IN THE ANNULAR SPACE OF A NaK-CONTAINING (WITHIN INNER CRUCIBLE) DOUBLE-WALLED IRRADIATION CAPSULE

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For the case of low heat-flow rates, control schemes may be based on (1) regulation of thermal radiation between the walls which form the annular space, and (2) control of conduction by the gas present in the space. If temperature levels are fixed, the amount of heat transferred by radiation depends on the emissivity factor in the radiation equation*. If stainless steel walls are present, the effective emissivity will be approximately 0.5. This can be changed if desired simply by using other materials. For example, aluminum, which has an emissivity of about 0.15, may be used as the cold wall to reduce the effective emissivity to 0.12. If mechanical considerations make it inconvenient to use aluminum as the container material, a snug-fitting aluminum sleeve can be inserted within an outer shell of another material such as stainless steel. Radiant heat transfer can also be altered by use of radiation baffles in the annular space.

Variation of heat flow by control of the conduction between the annulus walls is an important consideration. If the space is evacuated, the conduction heat is reduced to nearly zero. However, a better way of achieving a low rate of heat flow is through the use of argon, a low-thermal-conductivity gas, in the annulus. Considerably higher conduction rates may be obtained with helium, since it has roughly ten times the thermal conductivity of argon. Argon-helium mixtures can provide particularly fine control, since the variation of conductivity with composition is continuous, though not quite linear.

If the heat to be dissipated is higher than can be handled by helium in the thinnest practical annulus, it becomes necessary to employ metal fins that connect the inner crucible and the outer shell. From the heat-transfer viewpoint, the factors important in fin design are thickness, conductivity of materials used, and radial length. One problem introduced by fins is that of obtaining fin-wall joints which do not restrict heat flow or thermal expansion. Furnace-brazing techniques may be used to obtain metallurgically bonded joints. It is usually more satisfactory and much simpler, however, to design for assembly with a light press fit, which provides good thermal contact as the capsule expands on heating. Another minor problem with fins is temperature scalloping, the severity of which can be minimized by dividing the desired amount of heat-transfer material into the maximum number of fins consistent with good fabrication practices.

FACTORS RELATED TO TEMPERATURE DETERMINATIONS

Ideally, the temperature of an encapsulated heat-generating specimen should be measured by locating a thermocouple exactly at the point of interest, as at the surface or the center of the specimen. In the great majority of practical cases, however, such placement is not feasible without significantly modifying experimental conditions. In

*The radiation equation is $Q = C e (T_1^4 - T_2^4)$ where C is a constant, e is effective emissivity obtained by combining the individual wall emissivities into the factor $e = \left(\frac{1}{\frac{1}{e_1} + \frac{1}{e_2} - 1} \right)$, and T_1 and T_2 are wall temperature levels in absolute degrees.

these cases, the specimen-surface temperature may be calculated if a reference temperature is measured and the heat-transfer conditions between the reference point and the specimen surface are known. This can be seen from the simplified equation

$$T_s = T_o + QK , \quad (1)$$

where T_s is the specimen surface temperature, T_o is the reference temperature, Q is the specimen heat flux, and K is the resistance to heat flow between T_s and T_o , including a geometry factor which takes into account the corresponding length of heat-flow path. Of course, the accuracy with which T_s can be derived is dependent directly on the accuracy with which the terms in the above expression can be measured or calculated.

Reference-Temperature Measurements

Reference temperatures in radiation-capsule experiments may be obtained by adhering to fairly standard thermocouple techniques inasmuch as the thermoelectric characteristics of common materials such as Chromel, Alumel, copper, and constantan are not particularly affected by reactor radiation. High-temperature-alloy-sheathed ceramic-insulated thermocouple assemblies are particularly useful since they are commercial items, available in sizes as small as a sheath diameter of 40 mils. It is good practice in capsule work to locate the reference-temperature thermocouples as close as possible to the specimens. In this way T_o , a directly measured value, is large compared with QK , which is obtained indirectly. In a double-walled capsule, it is advantageous to locate thermocouples in the space between the specimen and the inner crucible. Close proximity to the specimen is thus achieved and, if a molten metal is present in the space, the couples are not affected by radiant heat. By using calibrated wire and precision instrumentation, the estimated two-sigma limit in T_o may be as low as ± 2 F.

Reference-Temperature Location

It is of little value to know a reference temperature to ± 2 F if the location of the point of reference is poorly known and is in a large temperature gradient. This is apt to be the situation in an irradiation experiment with a high specimen-heat generation. For example, consider the case of a long, cylindrical, fueled specimen, 158 mils in diameter, located in a NaK bath and generating 700 w per in. of length. This is consistent with the data presented in Figure 1 and the reference-capsule design discussed later in this report.

For this situation, the expression for the specimen surface temperature becomes

$$T_s = T_o + Q \cdot \frac{1}{2\pi k} \cdot \ln \frac{r_o}{r_s} , \quad (2)$$

where Q is the specimen heat per unit length, k is the thermal conductivity of the NaK, r_o is the radial distance from the center line of the specimen to the reference-temperature location, and r_s is the radius of the specimen at a point opposite the reference thermocouple. Taking an average value of 14 Btu/(hr)(ft)(F) for the thermal conductivity of the NaK, the temperature difference between the specimen surface and the reference thermocouple becomes 198 F. This sizable temperature difference is the result of a high specimen heat flux, a heat-transfer medium of moderately low thermal conductivity, and a small specimen diameter. It is immediately apparent that the four factors Q , k , r_o , and r_s must be known quite accurately or the error in the temperature difference will completely discount the precision with which the reference temperature itself can be measured.

The factor r_o in the above equation will depend upon:

- (1) The location of the specimen center line
- (2) The location of the reference thermocouple center line
- (3) The location of the effective junction within the thermocouple bead.

In normal practice, the specimen and thermocouple are supported and located independently from the ends of the capsule. Also, the specimen is allowed some freedom of movement to accommodate dimensional changes that accompany radiation damage. During capsule assembly and welding operations, the specimen and thermocouple can be expected to shift their positions somewhat; during the temperature rise to the operating level and as a result of radiation damage to the specimen, more distortion and changes in the location of the specimen and thermocouple can be expected. Under these circumstances, it is difficult to specify the location of the thermocouple with respect to the specimen center line any closer than ± 25 mils.

Not as obvious but of considerable importance is the uncertainty in the location of the effective thermocouple junction within the thermocouple bead. Unless carefully carried out, the common practice of fusing the thermocouple wires and the sheath together to form a bead can leave considerable doubt as to the location of the point at which the temperature is sensed. However, with care in forming the junction and radiographic inspection of the result, it is possible to establish the location of the junction with respect to the thermocouple center line within ± 3 mils.

Combining these limits we have a two-sigma limit of just slightly over ± 25 mils for r_o . * This by itself would create limits of ± 56 F or about ± 28 per cent for the temperature drop from the specimen surface to the reference thermocouple.

The variation in r_s is more difficult to predict. For the specimen being considered, a fabrication tolerance of only $\pm 1/2$ mil on the radius is specified. The only significant change in r_s will be an increase in diameter as a result of radiation damage. This is very difficult to treat in a manner similar to the other uncertainties since the change will always be in one direction and will vary with the type of specimen and time rather than as a random variation. Therefore, this analysis will treat the uncertainty

*Throughout this report, the estimated two-sigma limits are combined by the usual methods of finding the square root of the sum of the squares of the individual limits. The results can only be considered as engineering estimates since the individual limits are only estimates and the method of combination assumes, for lack of data, a normal distribution of values.

in r_s separately by finding the effect on the temperature measurement of a specified change in diameter during the experiment. For the specimen under consideration, a 5 per cent change in diameter will cause an 8 per cent change in the 198 F temperature difference which will mean a 16 F error in the predicted surface temperature.

Heat-Flow Determinations

The temperature drop from the specimen surface to the reference-temperature thermocouple is also dependent upon Q , the specimen heat flux. As has been explained in a previous section, the specimen heat will vary directly with the specimen fuel loading and the average thermal-neutron flux. The fuel loading can be controlled very closely. However, the neutron flux (and the specimen heat unless it is measured directly) will be uncertain to ± 20 per cent until the experiment is completed and the dosimeter wires can be examined. This is too late to be of use in calculating and controlling the specimen temperature. The ± 20 per cent estimated two-sigma limit for Q alone would mean an estimated two-sigma limit of ± 40 F in the specimen surface temperature.

A method of measuring heat flow directly and continuously during the irradiation exposure is proposed. It is believed that an applicable scheme is to use a differential thermocouple spanning a simple heat-flow path having precisely known thermal characteristics. One way would be to locate two thermocouples at different distances from the specimen in the NaK bath. However, thermocouple locations are usually subject to the uncertainties previously described. A better method of achieving the desired result is to install a differential thermocouple within a capsule wall so that it can measure a radial temperature difference across a well-defined distance of homogeneous material. While this distance may be short and the temperature drop correspondingly small, this limitation can be more than offset by the accuracy with which the thermocouple locations can be ascertained and with which the pertinent heat-transmission constants can be established. Furthermore, a single set of calibration data for a standardized heat-flow meter of this type can suffice for a variety of capsule applications. The design details of a typical device incorporated in a double-walled capsule are presented as part of a reference design described in a subsequent section.

It should be pointed out that, in order to arrive at a fission-heat-generation rate, two types of corrections must be applied to any physical measurement of radial heat flow. One is the subtraction of that fraction of the measured heat flux which is attributable to gamma heating of the specimen and the various capsule components. The second correction involves accounting for end losses (nonradial heat flow). In this connection, it is important to recognize that the radial heat flux may vary along the axis of the capsule, as a result of (1) nonuniform neutron flux, (2) axial variation in fuel concentration, (3) the use of fins (temperature scalloping), as well as (4) end losses. In a NaK-containing double-walled capsule, any variations caused by nonuniform fission-heat release [Items (1) and (2) above] tend to be smoothed out by the NaK. Even so, the use of a number of heat-flow meters spaced along the length of the capsule is desirable to provide an indication of whatever axial nonuniformity in heat flux may exist.

Other Factors

The remaining parameter of importance in the expression for the specimen-surface temperature is the thermal conductivity of the heat-transfer medium which, in the example being considered, is NaK. Actually, a small amount of convective heat transfer by the NaK must also be considered. However, this is normally very small and can be calculated and corrected for. With the best of current techniques, it should be possible to determine the thermal conductivity of NaK to ± 5 per cent which, in the situation described, will cause an uncertainty in the specimen surface temperature of about ± 10 F.

The foregoing discussions tacitly assume that radial variations in heat flow would not occur. This would be true if the fueled specimen being irradiated had a cylindrical symmetry and if the specimen were irradiated in an isotropic flux. In actual practice, of course, specimens of various configurations and flux patterns of various degrees of asymmetry may be encountered. Each of these presents special problems in the interpretation of specimen-surface temperatures from reference-temperature and heat-flow data. In fact, as soon as the specimen geometry departs from the ideal cylindrical shape, exact analytical solutions to the heat-transfer equations become difficult or impossible. Hence, when precise predictions of specimen temperature are required, it is necessary to utilize numerical methods or analog techniques.

In the design of an irradiation capsule some steps can be taken to improve the radial symmetry of heat dissipation even though the specimens are noncylindrical. For example, fins can be interrupted in low-heat-flux regions or partial heat-flow barriers can be introduced in high-heat-flux regions. Such practices, although difficult to implement without painstaking analytical or trial-and-error preirradiation procedures, can do much toward smoothing out specimen-temperature profiles which otherwise would be irregular.

Uncertainty in Specimen Temperature

The uncertainties in the factors discussed in the preceding sections and listed below can be combined to find an estimated two-sigma limit for the specimen-surface temperature for the example described.

	<u>Nominal Value</u>	<u>Estimated Two-Sigma Limits</u>	<u>Individual Effect on Temperature</u>
Reference-temperature measurement	1002 F	± 2 F	± 2 F
Reference-temperature location with respect to the specimen center line (r_0)	145 mils	± 25 mils	± 56 F
Heat flow	700 w per in.	± 20 per cent	± 40 F
NaK conductivity	14 Btu/(hr)(ft)(F)	± 5 per cent	± 10 F

The estimated two-sigma limit for the specimen-surface temperature is found to be ± 70 F as a result of these four factors. To this we may want to add the change of 16 F that would be caused by a 5 per cent change in specimen diameter as a result of radiation damage.

REFERENCE DESIGN

To illustrate how various factors related to heat transfer and temperature measurement can be handled in an actual capsule-design problem, a reference capsule was designed with the following basic stipulations:

- (1) A single uranium-10-w/o molybdenum stainless steel-clad cylindrical specimen is to be irradiated with a nominal surface temperature of 1200 F. The dimensions of the specimen are 0.158 in. in OD by 5-1/2 in. long (fueled length); the specimen is clad with 4 mils of stainless steel.
- (2) The maximum allowable capsule outside diameter is 1-1/8 in.
- (3) All-stainless steel construction is required.
- (4) A wide range of specimen-heat generations must be accommodated with a single basic design size. Fission heat is dependent on specimen enrichment and ambient neutron flux. For the specimen described above, the dependence of heat generation on flux and enrichment is illustrated in Figure 2.

With these rules in mind, a NaK-containing double-walled capsule which would be suitable for the reactor exposure envisioned from all viewpoints, including engineering and nuclear, was designed. The various details of the design formulated are presented in Figure 3. The comments below describe briefly features incorporated into the configuration because of heat-transfer considerations and the need for as precise a determination and control of the specimen temperature as possible.

Auxiliary Heating Element

The design is provided with an auxiliary heating element which is located within the liquid-metal-filled inner crucible space. The heater specified is a commercially available unit in which an MgO-insulated Kanthal wire with nickel lead wires is sheathed by a 1/16-in. -OD stainless steel tube 10 mils thick. The rated capacity of the heater that can be fitted into the space available is approximately 1-3/4 kw. Satisfactory furnace-brazing techniques are available for providing high-integrity seals at the points of entry of the heater and the thermocouples into the capsule.

During an actual experiment, the auxiliary heat produced would be regulated by a potentiometer controller actuated by a reference temperature.

FIGURE 2. HEAT GENERATION-EFFECTIVE FLUX RELATION FOR FUELED SPECIMEN USED IN REFERENCE DESIGN

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FIGURE 3. DETAILS OF A REFERENCE DESIGN OF AN IRRADIATION CAPSULE WITH AN INTERNAL HEAT-FLOW METER

All parts except purchased components to be of Type 304 stainless steel.

Heat-Flow Barrier in Annulus

Figure 1 shows how, for a capsule having fixed boundary temperatures and the same radial dimensions as those of the reference design, a wide range of heat-dissipation rates may be obtained by using various heat-flow barriers in the annulus. In the reference design, the fin dimensions and spacing shown in Figure 3 provide for the dissipation of approximately 0.7 kw per in. of length (3.85 kw total, exclusive of end losses), assuming that the liquid metal present is NaK.

A convenient way of providing these fins is to machine them integral with the inner crucible body. After the finned inner crucible has been assembled (loaded with liquid metal, specimen, thermocouples, and auxiliary heater) and sealed, it is telescoped into the outer shell assembly, using a light press fit.

Reference Thermocouples

As is shown in Figure 3, the six sheathed Chromel-Alumel thermocouples provided for reference-temperature measurements are equally spaced around the specimen. Their junctions are immersed in the liquid metal, two at each of three levels along the specimen length. To minimize placement uncertainties, which, as explained previously, give rise to corresponding uncertainties in specimen temperature, each thermocouple is positively positioned with respect to the specimen. This is accomplished by using special clips (visible in Figure 3) which hold the thermocouple center line at a fixed distance (~66 mils) from the surface of the specimen. These clips are light enough to prevent any restraint on the specimen upon blistering or swelling. Hot spots will not develop at the contacts because the areas of contact are tiny, and the thermal conductivity of the stainless steel clip is very close to that of NaK.

In a previous section, the uncertainty in the location of the thermocouples was discussed with reference to the center line of the specimen; in the capsule design discussed in this section, the thermocouple is located with reference to the surface of the specimen. An analysis of the sensitivity of the reference-temperature error to a change in the diameter of the specimen, $2r_s$, from radiation damage shows that, for the design under discussion, the error is much less if the thermocouple-positioning clip is designed to fix the thermocouple-to-specimen surface distance rather than the thermocouple-to-specimen center line distance. Strictly speaking, Equation (2) should now be written

$$T_s = T_o + Q \cdot \frac{1}{2\pi k} \cdot \ln \frac{(r_o - r_s) + r_s}{r_s} ,$$

or

$$= T_o + Q \cdot \frac{1}{2\pi k} \cdot \ln \left(\frac{r_o - r_s}{r_s} + 1 \right) . \quad (3)$$

The use of clips will reduce the uncertainty in the thermocouple center line-to-specimen surface distance to an estimated two-sigma limit of ± 5 mils or less. Combining this with the ± 3 -mil limit for the location of the junction within the thermocouple bead gives a two-sigma limit for $r_o - r_s$ of ± 6 mils and for $T_s - T_o$ of ± 7 per cent or ± 14 F, if there is no change in the specimen diameter.

The effect of a change in specimen diameter, $2r_s$, is calculated separately since, as mentioned previously, it is unidirectional and somewhat more predictable than the other, more randomly occurring, uncertainties. A change of 5 per cent in r_s , assuming $r_o - r_s$ is fixed by the thermocouple-positioning clip, will introduce an error of 3.8 per cent in $T_s - T_o$ and 8 F in the specimen-surface-temperature determination.

Differential Thermocouples for Heat-Flow Measurement

The differential thermocouples in the reference capsule are present to provide the means of obtaining direct measurements of radial heat flow. Three such devices are present - one at a location opposite the top portion of the specimen, one opposite the midpoint, and one opposite the bottom. Each heat-flow meter consists, in essence, of a pair of Chromel-Alumel thermocouples buried in the outer shell, with their junctions separated by 95 mils of stainless steel in the radial direction. They are connected so that their emfs oppose each other, the net output indicating the radial temperature drop across the span. For a radial heat flow of 700 w per in. of capsule length, the differential temperature would be about 80 F.

One method of simplifying the incorporation of these differential thermocouples into the outer shell assembly is to use three carefully fitted concentric cylinders telescoped together and furnace brazed. Before final assembly, axial grooves to accommodate the individually sheathed Chromel and Alumel wires are milled into the outer surfaces of the inner and central cylinders. These surfaces are then given a thin copper plate, the copper acting as the braze in the final assembly to insure a continuous radial heat-conduction path. Prior to telescoping the cylinders together, the sheathed and beaded Chromel and Alumel wires are laid into their grooves so that after brazing the sheath and bead are metallurgically bonded to sides and bottoms of the grooves. Thus, in place of the customary beaded thermocouple junctions, each junction is actually formed by a tiny, isothermal, circumferential span of stainless steel between the Chromel and the Alumel wires. The location of such a junction can be established by X-ray techniques to within a few mils and thus is well defined.

For maximum reliability, the differential-thermocouple heat-flow meter must be calibrated to provide a basis of correction for uncertainties such as end losses and gamma heating. With varying known inputs to the auxiliary heater, the relation between measured heat and gross heat input can be established. In the case of the reference design, a calibration corresponding to the entire fission-heat range anticipated would not be possible because of the limited capacity of the auxiliary heater provided. Calibration points up to the maximum capacity of the heater would be obtained, and the calibration in the upper range would be an extrapolation from these. Such an extrapolation could be made with confidence since there is no reason to expect discontinuities in the calibration curve. If desired, a correction for gamma heat can be

made on the basis of an in-pile calibration with an unfueled specimen. While prompt gammas could not be produced in such a situation, their contribution would be small if they were present.

By establishing the thermocouple-junction locations precisely and by taking into account corrections for end losses and gamma heating, it is believed that fission heat can be derived from differential-thermocouple measurements within ± 5 per cent without undue difficulty.

Uncertainties in Temperature and Heat-Flow Measurements

In a previous section, an analysis was presented of uncertainties in specimen-surface temperature in a sample capsule having radial dimensions matching those of the reference design shown in Figure 3. For a heat flow of 700 w per in. in a NaK-filled capsule the estimated two-sigma limit for the specimen-surface temperature was ± 70 F, neglecting a change in specimen diameter from radiation damage. In essence, the purpose of the reference design was to devise a configuration which would reduce this uncertainty significantly. This has been accomplished by (1) reducing the uncertainty resulting from the location of the reference-temperature point from ± 28 per cent to ± 7 per cent and (2) reducing the uncertainty in the heat generated in the specimens from ± 20 per cent to ± 5 per cent. If all of the uncertainties in the factors governing the determination of the specimen-surface temperature in the reference capsule (tabulated below) are combined, the estimated two-sigma limit for the specimen-surface temperature is ± 20 F. This is to be compared to the value of ± 70 F previously obtained.

	<u>Nominal Value</u>	<u>Estimated Two-Sigma Limits</u>	<u>Individual Effect on Temperature</u>
Reference-temperature measurement	1002 F	± 2 F	± 2 F
Reference-temperature location with respect to the specimen surface ($r_o - r_s$)	66 mils	± 6 mils	± 14 F
Heat flow	700 w per in.	± 5 per cent	± 10 F
NaK conductivity	14 Btu/(hr)(ft)(F)	± 5 per cent	± 10 F

It should be noted that the temperature determination will still be affected by a change in r_s , the specimen radius, from radiation damage. However, because of fixing the thermocouple with respect to the specimen surface with a positioning clip, a change in diameter of 5 per cent will introduce an error of only 8 F in the specimen-surface-temperature determination rather than the 16 F error obtained without a clip.

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