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ENGINEERING REVIEW OF STAINLESS STEEL
CLAD THERMOCOUPLE ELEMENTS

INTRODUCTION

As part of the overall program of evaluating the suitability of using ammonium hydroxide in place of lithium hydroxide, deposition of corrosion products (crud) on fuel element surfaces is a primary variable. To determine the crudding characteristics of ammonium hydroxide conditioned coolant, it is necessary to employ a fuel element with thermocouple(s) imbedded in it to measure the temperature drop between the water and the thermocouple.

The purpose of this report is to present an engineering review of the thermocouple elements to be used during the above evaluation.

SUMMARY AND CONCLUSIONS

To evaluate the crudding characteristics of ammonium hydroxide conditioned coolant it is necessary to use a thermocouple element. The present design has accentuated structural integrity, reliability and constant heat flux. A radical departure from past designs was made by selecting a stainless steel cladding and enriched ceramic fuel. Three thermocouples are inserted in the cladding to increase the reliability.

By the use of two thermocouple elements it will be possible to obtain important preliminary information on preferential crud deposition while simultaneously evaluating the crudding characteristics of ammonium hydroxide conditioned coolant.

DISCUSSION

Previous Tests

Previous thermocouple element designs have been based on NPR fuel element parameters with prototypical heat, beta and gamma fluxes, Zircaloy-2 cladding and metallic uranium fuel. In attempting to incorporate all of these variables the major problem is to obtain a proper balance between reliability, sensitivity and material compatibility.

To achieve maximum sensitivity it is necessary to minimize the temperature drop between the water and the thermocouple. This is achieved by placing the thermocouple either in the cladding or in the fuel adjacent to the clad. When Zircaloy-2 (Zr-2) cladding is used it is impractical to place the thermocouple in the cladding due to the excessive temperature drop and high core temperature. If the thermocouple is placed adjacent to the clad the thermocouple hole must be drilled since it is practically impossible to extrude the hole during initial fabrication. During irradiation the material adjacent to the hole becomes an area of high stress concentration that can lead to splitting of the Zr-2 clad. This actually occurred during a previous thermocouple element test.⁽¹⁾ After this failure this design was discarded. Subsequent designs have employed a single thermocouple imbedded in a Zr-2 core. Limiting the number of thermocouples and therefore the reliability.

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The area of material compatibility is a major problem if stainless steel thermocouples are used with Zr-2 clad elements. It is extremely difficult to effect a leak tight bond between stainless steel thermocouples and Zr-2 clad. By sacrificing sensitivity and reliability it appeared the material compatibility problem could be solved by brazing a Zr-2 clad thermocouple into a Zr-2 core. (Figure 1) During ex-reactor testing of this design it was discovered that there was a serious problem with internal cracking of the Zr-2 clad thermocouples. This problem could not be satisfactorily rectified and further work on this design is contingent on reception of satisfactory thermocouples.

PRESENT DESIGN

To circumvent the problem of material compatibility, an all stainless steel system was selected. This eliminates the problem of dissimilar materials at critical joints. The design criteria for the thermocouple elements were as follows:

1. To increase the structural integrity over previous designs.
2. To obtain maximum reliability without sacrificing sensitivity.
3. To maintain a constant or as near constant a heat flux as possible during the test.

To minimize the possibility of having the coolant contact the fuel material, the element was designed so that there would be only one possible opening - where the fuel is inserted. The endcap and cladding are made of stainless steel to minimize closure problems. This eliminates the problem experienced in some previous designs of effecting a leak tight seal between stainless steel and Zr-2.

There are two types of stainless steel suitable for cladding material - ASTM Type 310 and 416. These are the only two stainless steels that do not react with uranium oxide at elevated temperatures.⁽²⁾ Experiments conducted during the development of the "Dynapak" process - a high energy compaction technique - demonstrated that uranium oxide and Types 310 and 416 stainless steel were compatible to 1200 C. There is no experimental information above this temperature, therefore this temperature was chosen as the limiting case for the stainless steel - uranium oxide interface temperature.

Type 416 cladding is more sensitive and less prone to stress cracking because of its higher thermal conductivity and lower thermal expansion. However Type 416 is generally considered non-weldable because of its tendency to split along the weld bead while cooling. By employing special pre-and post-welding heat treatments Type 416 can be welded, however, the integrity of the weld is questionable. To maintain Hanford safety standards it is impossible to weld Type 416 clad thermocouple elements without major modifications to existing facilities. For these reasons Type 310 was chosen for the cladding material.

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Type 310 stainless steel is a high chrome, high nickel steel. Its corrosion resistance in high temperature pH 10 conditioned water is excellent - approximately 0.04 mils/year. Combined with its resistance to oxidization, it has high strength at elevated temperatures - the maximum temperature for continuous operation in air is 2100 F. It is also very ductile and readily weldable. All of these characteristics make it suitable for thermocouple element cladding.

The reliability was increased by placing three thermocouples in the cladding. Previous experience has shown one out of three thermocouples is usually damaged in some way during the in-reactor test. Presently two designs are being considered differing in placement of the thermocouple and the addition of a Zr-2 jacket. Cross section views of these two designs are shown in Figure 2. The design in Figure 2a has a temperature drop of 232°C from the bulk water temperature to the midpoint of the thermocouple, and Figure 2b a corresponding temperature drop of 187°C . These temperature drops are approximately one half of the expected temperature drop of the element shown in Figure 1. By cutting the temperature drop in half the sensitivity to crud detection is doubled.

One very important improvement over previous designs is the lack of catastrophic consequences if a leak develops at the thermocouple seal. In metallic uranium thermocouple elements such a leak would produce a rupture by either allowing the coolant to contact the uranium, or by hydriding the Zr-2 core and caps so severely a rupture would eventually result. By employing a thickwalled stainless steel cladding there is sufficient cladding between the thermocouple and the fuel to insure that a water leak at this point will not result in a rupture. Hence a leak at the thermocouple seal will not compromise the structural integrity of the element. The worst case for this situation is a loss of the thermocouple, however, a failure of this type is unlikely.

The fuel material selected is enriched uranium oxide powder. The desired density of $85\% + 1\%$ (10 g/cc) of theoretical is achieved by packing the powder into the element with an electric hammer. To achieve a $600,000 \text{ Btu/hr-ft}^2$ heat flux, 4.5 w/o U^{235} is used. The calculated burnup rate for these elements is 0.06 percent/full power day. This corresponds to a five percent change in heat flux for two reactor operating periods ($600,000 \text{ Btu/hr-ft}^2$ to $570,000 \text{ Btu/hr-ft}^2$) which closely approximates a constant heat flux. (See Tables I and II for the heat flux vs enrichment data and engineering data for this design.) Without a constant heat flux the measured temperature drop will decrease during the test. With this condition there is no base experimental relationship to measure the increase in temperature drop due to crud deposition.

The literature is rather devoid of information on preferential deposition of crud on Zr-2 and stainless steel fuel element surfaces. Hence it is desirable to run one thermocouple element without a Zr-2 jacket to obtain preliminary information on this subject. Although the primary reason for this test is to evaluate the crudding characteristics of ammonium hydroxide conditioned coolant, any information obtained on preferential deposition would aid the development of future thermocouple elements.

To summarize the advantages of this type of thermocouple element:

1. Increased structural integrity over previous designs by using a stainless steel cladding and end caps, hence eliminating the problem of different materials at critical joints.

FIGURE 1

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2a Expected Temperature
Drop 232°C

2b Expected Temperature
Drop 187°C

FIGURE 2

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REFERENCES

1. Call, R.L., Development of a Thermocoupled Fuel Element for Measuring Fuel Temperature In-Reactor, July 31, 1962, HW-74482. SECRET
2. Personal Communication with L. C. Lemon March 19, 1962.

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TABLE I

<u>Percent Enrichment</u>	<u>Surface Heat Flux (Btu/hr-ft²)</u>
3	425,000
6	748,000
9	931,000

TABLE II

Overall Length	6 3/4 in.
Fuel Length	6 in.
Zr-2 Jacket OD-ID	1.412 x 1.382 in.
S/S Clad OD-ID	1.382 x 0.925 in.
Fuel OD	0.925 in.
Fuel Enrichment	4.5 w/o U ²³⁵
Type of Fuel	Enriched UO ₂ powder
Loading Method	Compaction
Theoretical Density	85% + 1% (10 g/cc)
Weight of Uranium Oxide	664 grams
Design Surface Heat Flux	600,000 Btu/hr-ft ²
Power of Element	32 KW
Burnup Rate	0.06%/full power day
Maximum Fuel Temperature	3200 C
Minimum Fuel Temperature	920 C
Average Fuel Temperature	2300 C
Temperature Drop Through Cladding	572 C
S/S - UO ₂ Interface Temperature	
a. S/S Clad	886 C
b. Zr-2 Jacket, S/S Clad	996 C
Temperature Drop to Mid-point of Thermo-	
couple	
a. S/S Clad	187 C
b. Zr-2 Jacket, S/S Clad	232 C
Support Ring Diameter With C/S Shoes	2.002 in
Thermocouples	3, 1/16" S/S Clad
Thermocouple Sealing Mechanism	Modified S/S Swagelok

Note: All power calculations are based on an adjacent tube power of 79.3 KW/foot.

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NOMENCLATURE

A	Area (ft^2)
C _p	Specific heat ($\text{Btu}/\text{lb}^\circ\text{F}$)
D _e	Equivalent diameter (ft)
G	Mass flow rate ($\text{lb}/\text{hr}\text{-ft}^2$)
h	Heat transfer coefficient ($\text{Btu}/\text{hr}\text{-ft}^2\text{-}^\circ\text{F}$)
h ₁	Heat transfer coefficient across the water film
h ₃	Heat transfer coefficient across the Zr-2, S/S interface
K	Thermal conductivity ($\text{Btu}/\text{hr}\text{-ft-}^\circ\text{F}$)
K ₂	Thermal conductivity of Zr-2
K ₄	Thermal conductivity of S/S
N _{Re}	Reynolds number
N _{Pr}	Prandtl number
q	Heat rate (Btu/hr)
ΔT	Temperature drop
U	Overall heat transfer coefficient ($\text{Btu}/\text{hr}\text{-ft}^2\text{-}^\circ\text{F}$)
ΔX_2	Distance through Zr-2 jacket (ft)
ΔX_4	Distance through S/S cladding (ft)
μ	Viscosity ($\text{lb}/\text{ft}\text{-hr}$)

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APPENDIX

DATA

Flow rate	40,000 lb/hr
Process Tube Diameter	2.028 in
Velocity	7.9 ft/sec
Design Surface Heat Flux	
Equivalent Diameter	0.0505 ft
Cross Section	0.0116 ft ²
Mass Flow Rate	3.45 x 10 ⁶ lb/hr-ft ²
Viscosity KER-1 conditions	0.24 lb/ft-hr
K _{Zr-2}	9.68 Btu/hr-ft ² -°F
K S/S - 500 C	10.8 Btu/hr-ft ² -°F
K S/S - 500-1200°C avg.	13.5 Btu/hr-ft ² -°F
K Water KER-1 Conditions	0.354 Btu/hr-ft ² -°F
h ₃ Zr-2 - S/S Interface	5,000 Btu/hr-ft ² -°F

$$\text{Reynolds Number } \frac{DeG}{\mu} = \frac{0.0505 \times 3.45 \times 10^6}{0.24} = 7.25 \times 10^5$$

$$\text{Prandtl Number } \frac{C_p \mu}{K} = 0.85$$

For Annuli

$$h \text{ De} = 0.023 (N_{Re})^{0.8} (N_{Pr})^{0.4}$$

solving for h

$$h_1 = \frac{0.023 (N_{Re})^{0.8} (N_{Pr})^{0.4} K}{De}$$

Substituting

$$h_1 = \frac{0.023 (7.25 \times 10^5)^{0.8} \times (0.85)^{0.4} \times 0.354}{0.0505}$$

$$h_1 = 7,850 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

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Case 1 Zr-2 jacket thermocouple adjacent to the jacket as in Figure 2a.

Assumption: The "wall thickness" from the Zr-2 jacket to the midpoint of the thermocouple is sufficiently thin to assume constant area.

Total Resistance:

$$\frac{1}{U} = \frac{1}{h_1} + \frac{\Delta X_2}{K_2} + \frac{1}{h_3} \frac{\Delta X_4}{K_4}$$

$q = U \Delta T$ rearranging and substituting

$$\Delta T = 600,000 \left[\frac{1}{7,850} + \frac{0.00125}{9.68} + \frac{1}{5,000} \frac{0.0026}{10.8} \right]$$

$$\Delta T = 232^\circ \text{C} \leftarrow$$

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Case 2

No Zr-2 jacket - Distance from OD of S/S clad to midpoint of the thermocouple 1/16 inch.

Constant Area will be assumed again.

$$\frac{1}{U} = \frac{1}{h_1} + \frac{\Delta X_4}{K_4}$$

$$\Delta T = 600,000 \left[\frac{1}{7,850} + \frac{0.0052}{10.8} \right]$$

$$\Delta T = 187^{\circ}\text{C}$$

Interface Temperature UO_2 to S/S

Calculate the temperature drop across the S/S cladding

$$\Delta T = \frac{8}{277LK_4} \ln \frac{X_2}{X_1}$$

$$q = (q/A)A = 600,000 \text{ } \gamma \text{ DL}$$

$$X_1 = \text{Clad ID} = 0.925$$

$$X_2 = \text{Clad OD} = 1.382$$

Substituting:

$$\Delta T = \frac{6 \times 10^5 \times 1.382}{2 \times 12 \times 13.5} \ln \frac{1.382}{0.925}$$

$$\Delta T = 572^{\circ}\text{C}$$

For the Zr-2 jacketed element the temperature drop through the Zr-2 jacket and across the Zr-2 - S/S interface is 110 C.

Based on a controlling surface of 314 C the interface temperatures would be 886 C and 996 C respectively for the stainless clad and Zr-2 jacketed elements. Both of the above temperatures are below the 1200 C limit.

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