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APPARATUS TO SIMULATE NUCLEAR HEATING IN ADVANCED FUELS

by

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TABLE OF CONTENTS

	<u>Page</u>
Abstract	1
1 Introduction	1
2 Development of DEH apparatus	1
2.1 Specimen holder	2
2.2 Power supply	5
2.3 Electrical controls	6
2.4 Instrumentation	7
2.5 Electrode design	8
2.6 Length measurement and calibration	8
3 Results	9
4 Summary and conclusions	14
Acknowledgments	15
References	15

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Complete DEH apparatus	3
2.	Schematic of DEH specimen holder and instrumentation	4
3.	DEH specimen holder	4
4.	Schematic of electrical components of advanced fuels DEH apparatus	5
5.	Thermal expansion of UC as a function of temperature	9
6.	Buckled UC pellet photographed during cool-down	11
7.	Scanning-electron micrograph showing cross-sectional view and void due to melting in UC pellet tested in DEH apparatus	11
8.	Magnified view of fusion zone in Fig. 7 showing extent of cracking in center of UC pellet	12
9.	Scanning-electron micrograph showing extent of cracking on surface of UC pellet	12
10.	Optical macrograph of UC pellet showing microstructure and large fusion zone	13

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Abstract

A direct-electrical-heating apparatus has been built to simulate in-reactor temperature gradients and heating conditions in both the mixed nitrides and carbides of uranium and plutonium. The apparatus has the capability for the investigation and direct observation of fuel-behavior phenomena that should significantly enlarge the data base on mixed carbides and nitrides at temperatures near and above their melting points. In addition to heating UC, results of proof tests showed that the apparatus has the capability to heat graphite, 30 vol % ZrC in graphite, B₄C control-rod pellets, and stainless steel.

1. Introduction

A direct-electrical-heating (DEH) apparatus has been designed and constructed to investigate the mechanical response of advanced fuels to thermal transients that simulate in-reactor accident conditions. A phenomenological understanding can thereby be developed for the interaction between solid and molten fuel, fuel vapor, and fission products during rapid heating.

The development of a DEH apparatus that simulates in-reactor heating conditions of advanced fuels is described. The results of the preliminary proof tests on UC, (U,Zr)C in graphite, B₄C, and stainless steel are also included to verify the capabilities of the apparatus.

2. Development of DEH apparatus

Similar DEH equipment to simulate in-reactor heating conditions in UO₂ and irradiated¹ (U,Pu)O₂ has been described in preliminary² and updated^{3,4} reports. Although the instrumentation of the UO₂ DEH apparatus

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is the same as that used in the UC DEH apparatus, the electrical resistance of UO_2 at room temperature is several orders of magnitude higher than that of UC and UN. The electrical conductivity of UC and UN are quite similar from room temperature to 1600 K. Thus, the design of the power supply and specimen chamber of the UC DEH apparatus are significantly different from the UO_2 DEH apparatus. In addition, the higher thermal conductivity of carbide/nitride fuels, compared with UO_2 , contributes to a large difference in the response of the fuel to applied transients.

The thermal simulation apparatus was designed to provide direct visual observation of fuel-fission-gas phenomena associated with transient over-power or loss-of-flow thermal transients. It utilizes the ohmic heating of carbide or nitride fuel. The apparatus has the capability to operate in both steady-state and transient heating modes, and heating rates of 2500 K/s are within the capabilities of both the electronics and the response times of the power supply.

2.1. *Specimen holder*

The complete DEH apparatus is shown in Fig. 1, and a schematic of the specimen holder with instrumentation is shown in Fig. 2. The holder consists of upper and lower water-cooled tungsten electrodes fitted into water-cooled stainless steel electrode guides. The upper and lower stainless steel electrode guides are attached to a phenol fiber material* that electrically insulates the specimen holder from the metal stand which supports the apparatus. The electrode guides are fitted with O-ring seals to form a gas-tight seal with the clear quartz cylinder. Thus, as is shown in Figs. 1 and 3, the pellet-stack test specimen can be directly observed, and infrared radiation pyrometry can be utilized to monitor and continuously record sample surface temperature. The upper electrode is spring loaded to accommodate axial displacements during temperature-cycling experiments.

The test section is cooled continuously by flowing high-purity helium gas. Changes in specimen surface temperature can be achieved by modifying the flow rate and varying the diameter of the

*Trade name G-10, manufactured by Synthane Technical Plastics Company.

Fig. 1. Complete DEH apparatus. Neg. No. ANL-306-75-168K.

Fig. 2. Schematic of DEH specimen holder and instrumentation.
Neg. No. MSD-62090.

Fig. 3. DEH specimen holder.
Neg. No. MSD-61002.

inner, clear quartz cylinder, which provides an annular gap to channel the coolant gas. Pellet surface temperatures have been decreased by ~ 900 K as the helium flow rate increased from 0.1 to ~ 14 cfm; higher flow rates are possible. The electrical and thermal conductivities⁵ of UC and UN are so similar that the same temperature gradients can be expected for experiments using UN fuel.

2.2. Power supply

At room temperature, the electrical resistance of UO_2 is high, and, as the temperature increases, the resistivity decreases continuously. The opposite effect is observed in carbide fuels, i.e., the resistivity increases with temperature. This difference has necessitated the design and construction of a modified power supply. Figure 4 shows that the power supply operates only in a low-voltage, high-current (50 V, 2000 A) mode.

Fig. 4. Schematic of electrical components of advanced fuels DEH apparatus. Neg. No. MSD-63608.

The power supply for the advanced fuels apparatus had original design limits of 50-V direct current (dc) at 1500-A dc. In actual practice, the power supply has operated at 2000 A and reduced voltage. Design of the power supply was achieved in a straightforward manner and used purchased items where possible. Three-phase line power of 440 V alternating current is phase back-controlled by the silicon control rectifier unit and applied to the delta-connected primary of the three-phase power transformer. The secondary is also delta connected and is wired to the three-phase, full-wave bridge rectifier system (air cooled). The unfiltered dc output from the bridge is then filtered by a single inductance-capacitance filter and brought out to the output terminals of the main power supply. Direct current is used because we think it is easier to control, and only a routine effort is required to achieve this output mode.

2.3. Electrical controls

A voltage limiter, power limiter, and two current limiters that automatically engage and assume control when either the voltage or current preset control levels are reached are important features of the electrical control system. Indicator lights are installed adjacent to the limiters to inform the operator which mode of control is operative at all times. The two current limiters are utilized to initiate the transient phase of the experiment. The procedure is to preset the power, voltage, and current limiter number 2 at high levels and control the electrical power with current limiter number 1. The power can then be varied by switching to current limiter 2, which automatically disengages current limiter 1 and calls for the higher power level preset on current limiter 2. The purpose of the Data-Trak controller (Fig. 4) is to perform reproducible pretransient heat-ups.

A timer has been installed so that the switch (current limiter 2) initiating the transient simultaneously starts the timer. Power is automatically terminated when the preset time has been attained. The timer

is convenient for running interrupted experiments designed to focus on an event occurring at some time predetermined from a previous test or to follow phenomenon development.

Heating rate is an important parameter for transient experiments. Therefore, a transient-rate selector was incorporated into the system to achieve reproducible power ramps at rates that can be varied as desired.

2.4. Instrumentation

Slumping of the fuel (i.e., stack-length reduction) was monitored by a Linear Variable Differential Transformer (LVDT)* connected to a high-speed recorder.** The LVDT was calibrated with optical micrometers sighted on the top and bottom extremes of the pellet stack. In addition to the amount of expansion during heating and contraction during slumping, the LVDT also gave a numerical value to the rate at which slumping occurred because of its rapid response time.

Following gross fuel motion in which fuel slumping exceeds the ~0.33-cm travel of the upper electrode with its attached LVDT extension arm, arcing usually occurs across the gap between the pellet stack and the upper electrode, if the input power is not instantaneously shut off. This arcing can lead to larger melt fractions than were actually achieved during the test. To eliminate the necessity for rapid human response, the LVDT has been incorporated into the system so that, when the ~0.33-cm maximum LVDT travel is exceeded, a contact is opened in the LVDT power supply. When this contact opens, the input power to the pellet stack is automatically shut off. In addition, a limit switch has been incorporated into the system so that the maximum LVDT travel to instantly terminate the input power can be easily adjusted from 0.003 to 0.64 cm.

Acoustic-emission detection is being used with the DEH apparatus. Acoustic-emission transducers permit the detection of low-intensity sounds that occur during thermal-shock cracking (Fig. 1). Preliminary tests indicate that this technique will be useful in gaining an insight into the

* Daytronic Corp. Model 103C-200.

** Honeywell 1858 CRT Visicorder.

role of cracking during either accident simulation or thermal-cycling experiments below the failure threshold.

Changes in axial forces during heating and cooling can be measured using the load cell attached to the bottom electrode holder (Fig. 1). In this case, the upper electrode is stationary, and the lower electrode is free to move during expansion and contraction of the pellet stack.

A high-speed movie camera with 16-mm color movie film is used to record fuel motion during rapid transients. The camera speed can be varied from 24 to 12,000 frames/s, but generally a speed of 1000-2000 frames/s is used. Since the high-speed camera has a short lag time before attaining its preset speed level, the camera is started before the transient is initiated. To synchronize the start of the transient on both the recorder and movie, the switch (current limiter 2) which initiates the transient is wired so that a single flash (1/1000-s duration) is given off by a flash attachment to mark the film at the start of the accident. In addition, a second flash attachment has been wired to flash when the power is automatically terminated to mark the end of the transient on the movie film.

2.5. Electrode design

The upper electrode of the prototype apparatus has been designed so that the clamp for the electrical connection is a removable disk-shape platform. This platform is then loaded with a metal beaker containing lead spheres so that the load on the pellets can be conveniently varied by introducing or removing lead spheres from the beaker.

2.6. Length measurement and calibration

Unclad, solid UC pellets were used to calibrate the changes in length measured with the LVDT. The upper water-cooled electrode was spring loaded, and the expansion and contraction of the pellet stacks were monitored by clamping a Micarta extension arm to the electrode and measuring the displacement of the Micarta extension arm by means of the LVDT.

The pellets were heated to ~1500 K, and the measurements of length changes were recorded. Simultaneously, the changes in length were measured optically with two cathetometers sighted on the top and bottom extremes of

the pellet stack. The LVDT readings were within ± 0.003 cm of the optical micrometer readings. This close agreement was obtained because both electrodes were water cooled, which minimized expansion from sources other than the specimens.

During the accident portion of the experiments, the slumping of the fuel (i.e., stack-length reduction), the total length change, and, more importantly, the rate at which the pellet stack slumped were measured by the LVDT.

3. Results

Figure 5 shows the thermal expansion of UC as a function of experimentally measured surface temperature (centerline temperatures are ~ 100 K higher), and the data are in good agreement with the curve derived by Andrew⁶ in a review of thermal-expansion data. The DEH curve needs to be verified by more experiments to determine the reason for the poor data agreement at temperatures above 1200 K. The present results were measured optically and were used to calibrate the LVDT.

Fig. 5. Thermal expansion of UC as a function of temperature.
Neg. No. MSD-63607.

Large quantities of UC pellets for the DEH program, which are used to investigate the mechanical response of the fuel to applied transients, were not available. However, two UC pellets were acquired for test purposes, and it was decided to maximize the information obtained by performing mechanical-response experiments at the two expected extremes of applied transients. Thus, the objective of the first test was to study the fuel behavior prior to the occurrence of gross fuel motion, whereas the second pellet was tested well past the failure threshold.

An analysis of the preliminary experiments has been completed, and qualitative observations of UC fuel response have been made. For the pellet tested below the failure threshold at an average energy-deposition rate of ~ 1000 J/g-s, the acoustic-emission transducers detected the occurrence of cracking during the pretransient heat-up to $\sim 1200^\circ\text{C}$ and during the transient. Based on similar acoustic signals recorded during parallel experiments performed on UO_2 pellets, it was expected that microcracks in the UC would be found on posttest visual examination. The expectation of finding UC microcracks as opposed to macrocracks was supported by the fact that cracks could not be heard or observed forming during the test, whereas in UO_2 tests, cracking sounds are heard and large cracks are observed. The cracks in the UC pellets were not easily detected visually as expected, and scanning-electron microscopy was required to verify the existence of microcracks. Figure 6 shows the heated pellet that buckled during the experiment. Figure 7 shows the large central void in the pellet that is due to fuel melting. Figure 8 is a magnified view of the fusion zone and shows extensive cracking that appears during cool-down. Figure 9 shows the extent of cracking on the UC pellet surface, which for UO_2 would be easily observed visually. Figure 10 is a radial cross section of the pellet showing the large melt fraction, with some solidified UC on the outer radius of the pellet. Also, the original grain structure is shown, and a change in stoichiometry appears to have occurred in the fusion zone. A stoichiometry change is suspected because only the central melt zone is affected. Another possibility is that the fusion zone contains oxidized uranium. Since high-purity helium was used in the test, the entire sample would be expected to oxidize starting at the free surface of the UC pellet.

Fig. 6. Buckled UC pellet photographed during cool-down. Neg. No. ANL-306-75-163K.

Fig. 7. Scanning-electron micrograph showing cross-sectional view and void due to melting in UC pellet tested in DEH apparatus. Mag. 9X. Neg. No. MSD-62065.

Fig. 8. Magnified view of fusion zone in Fig. 7 showing extent of cracking in center of UC pellet. Mag. 40X. Neg. No. MSD-62067.

Fig. 9. Scanning-electron micrograph showing extent of cracking on surface of UC pellet. Mag. 42X. Neg. No. MSD-62066.

Fig. 10. Optical macrograph of UC pellet showing microstructure and large fusion zone. Neg. No. MSD-62256.

A load of ~ 2 kg was maintained on the per electrode. A fuel-deformation rate (analogous to a nonisothermal creep rate) of $\sim 0.1 \text{ s}^{-1}$ was recorded while the fuel surface temperature exceeded 2670 K and the fuel center was partly molten. Because of uncertainties in the temperature gradient, it is difficult to compare the deformation rate obtained from one UC test to rates measured for UO_2 . However, future tests could be designed to determine deformation rates at temperatures approaching the melting point of UC.

The second UC pellet was tested at an average energy-deposition rate of $\sim 1900 \text{ J/g-s}$, and, except for a small portion of UC adjacent to the electrodes, the entire sample melted in 1.8 s. Acoustic-emission data were not recorded for this test because of a malfunction of the acoustic signal detector.

The high-speed movies of this experiment showed that violent molten fuel dispersal occurred at ~ 1.6 s, and again at 1.7 s, after the start of the power transient. The test was automatically terminated after 1.8 s by the LVDT, which was set to respond to fuel motion in this manner. The

importance of the cracks in a fuel undergoing a transient is that they act as escape paths for molten fuel. However, narrow-width microcracks, such as those found thus far in UC, do not offer a significant escape path, and the molten fuel is trapped by the solid outer region of UC. This results in pressure buildup due to the fuel-volume increase on melting and UC vapor generation with a subsequent explosive-type fuel failure.

These tests have shown that the DEH apparatus has excellent potential for investigating and directly observing fuel-behavior phenomena, which should significantly enlarge the modeling data base on UC at temperatures near and above the melting point of UC.

In addition to UC, proof tests have been performed on graphite, 30 vol % ZrC in graphite, B_4C control-rod pellets, and stainless steel to verify that certain basic requirements of the apparatus could be achieved. All specimens have been successfully heated to uniform, steady-state surface temperatures. Pellet surface temperatures can be decreased by $\sim 600^\circ C$ by increasing the helium flow rate from 0.1 to ~ 14 cfm, and higher flow rates are possible. Steady-state operation was achieved for periods of hours with no significant power fluctuations. Rapid power cycling of UC pellets between room temperature and a fuel surface temperature of $1000^\circ C$ resulted in extensive surface cracking and some microcracking, with no effect on electrical continuity. Therefore, no problems are foreseen when cracked preirradiated fuel is used.

4. Summary and conclusions

A DEH apparatus has been built that simulates in-reactor temperature gradients and heating rates in carbide and nitride nuclear fuels, both of which have similar electrical and thermal conductivities. The apparatus is capable of investigating the mechanical response of these fuels at temperatures near and above their melting point, during both steady-state and rapid transient-heating experiments. In addition, the apparatus has similar steady-state and transient capabilities for heating graphite, 30 vol % ZrC in graphite, B_4C control-rod pellets, and stainless steel rod or tubing.

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