FUEL-CLADDING MECHANICAL INTERACTION
AND GAS PRESSURE BUILDUP IN A
SHORTENED FTR-TYPE FUEL PIN

R. B. Fitts
B. Fleischer
R. L. Senn

MASTER

BLANK PAGE

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22151
Price: Printed Copy \$5.45; Microfiche \$0.95

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

ORNL-4875
UC-79b - Liquid Metal Fast Breeder Reactors
(Fuels and Materials Engineering and Development)

Contract No. W-7405-eng-26

METALS AND CERAMICS DIVISION

FUEL-CLADDING MECHANICAL INTERACTION AND GAS PRESSURE BUILDUP
IN A SHORTENED FTR-TYPE FUEL PIN

R. B. Fitts, B. Fleischer, and R. L. Senn

JUNE 1973

-NOTICE-

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
U.S. ATOMIC ENERGY COMMISSION

MASTER

CONTENTS

	<u>Page</u>
Abstract	1
1. Introduction	1
2. Objective	2
3. Experimental Plan	2
4. Description of Equipment	3
4.1 Mechanical Design and Instrumentation	3
Motion Transducers	5
Integral Calibration System	5
Gas Pressure Measurement System	6
Thermocouples	6
Flux Monitoring Guide	7
4.2 Thermal Design	7
5. Special Fabrication	10
5.1 Fuel Element	10
Fuel Material	10
Cladding	12
Fuel Element Assembly	12
5.2 Capsule Brazements	13
6. Data	13
6.1 Operating Data	13
6.2 Neutron Radiography	19
7. Instrumentation Problems	21
7.1 Calibration Solenoid Operation	21
7.2 Motion Transducer Temperature	21
7.3 Motion Transducer Failures	22
7.4 Irregular Motion Indications	23
7.5 Flux Monitor Experience	24
8. Discussion of Results	25
8.1 Internal Gas Pressure	25
8.2 Fuel Column Length	27
Contraction at Power	28
Growth at Constant Power	29

BLANK PAGE

Thermal Expansion	30
8.3 Cladding Behavior	30
8.4 Mechanical Interaction	32
9. Conclusions and Recommendations	32
Acknowledgments	34
References	35
Appendices	
A. Calibration of Motion Transducers	41
B. List of Engineering Drawings	49
C. HEATING3 Thermal Analysis	53
D. Fuel Data	61
E. Bulkhead Braze Specification MET-FCT-PP-42	69
F. Primary Container-Thermocouple Braze Assembly Specification MET-FCT-PP-38	77
G. Computation Method for Estimating the Average Surface Temperature Along the Cladding	85
H. Correlations of Thermocouple and Transducer Coil Temperatures	91
I. Gas Release and Burnup Calculations	97

FUEL-CLADDING MECHANICAL INTERACTION AND GAS PRESSURE BUILDUP IN A SHORTENED FTR-TYPE FUEL PIN

R. B. Pitts, B. Fleischer, and R. L. Senn*

ABSTRACT

The design and operation of an experiment (MINT-1) to evaluate fuel-cladding interaction and gas pressure buildup in a prototype FTR fuel pin is described. The capsule was instrumented to measure fuel and cladding length, internal gas pressure in the fuel pin, and cladding temperature. The test fuel pin was a shortened FTR-type (U,Pu)O₂ pin with type 316 stainless steel cladding. The capsule was designed to operate at controlled, continuously variable fuel pin powers from 0 to 19.5 kW/ft with corresponding cladding midwall temperatures up to 700°C.

The data on fuel pin performance indicated, as expected, that mechanical interaction will not be a problem in the FTR fuel pin at the low burnup (1.7% FIMA) achieved in this test. Cladding thermal expansion was uniform and predictable on the basis of existing data. Fuel thermal expansion was less uniform but always fell between the expansion calculated on the basis of fuel pellet surface temperature and that calculated on the basis of the temperature at the inner edge of the end dish on the pellet with an expansion coefficient of $10 \times 10^{-6}/^{\circ}\text{C}$. During operation at constant power the fuel first contracted because of creep or sintering and then expanded with burnup accumulation. The release of fission gases from the fuel depended upon power level and history but was not affected by power cycling.

1. INTRODUCTION

The possibility of failure of fuel elements through the processes known as "mechanical interaction" has become an important consideration in assessing the life of metal-clad pellet-type fuel elements.¹⁻⁸ The term "mechanical interaction" is used to describe the presence of forces developed by contact between fuel pellets and cladding during operation

*Reactor Division.

of the fuel pin. Such forces can be sufficient to cause yielding of the cladding and eventual failure. The physical factors that influence mechanical interaction are the thermal expansion characteristics of the fuel and cladding, swelling of fuel and cladding, fuel pellet geometry, and the fuel-to-cladding gap size. Operation variables such as temperature distributions, heat-up rates, cool-down rates, and burnup directly affect the above factors and therefore must be given proper consideration in evaluating mechanical interaction in any particular fuel element.

A test of the MINT type has the potential for yielding performance information in a variety of areas for any fuel pin design and set of operating conditions. Some of the more important of these areas are:

1. the occurrence and severity of fuel-cladding mechanical interaction,
2. the rate of fuel-cladding gap closure,
3. the reliability of fuel thermal expansion, and
4. the mode and rate of fission gas pressure buildup.

2. OBJECTIVE

The main objective of this experiment was to evaluate the fuel element planned for the Fast Flux Test Facility reactor (FTR) with respect to mechanical interaction and fission gas pressure buildup. The development of an instrumented capsule capable of detecting mechanical interaction during test and monitoring the principal test variables was an important secondary objective. Our capsule, therefore, contained necessary instrumentation for monitoring cladding temperature, differential axial expansion between the fuel column and cladding, fuel column expansion, and gas pressure inside the fuel element. We provided for periodically measuring the axial flux profile.

3. EXPERIMENTAL PLAN

Our general test plan called for operation of a series of irradiation test capsules in the poolside facility of the Oak Ridge Research Reactor (ORR).⁹ This initial experiment (MINT-1) was designed to develop our basic test equipment and to evaluate a "typical" FTR fuel element.

Typical in this case was defined to be a fuel element whose dimensions and makeup were in the middle of the range allowed by specifications for the FTR fuel element. Furthermore, "typical" as applied to operating parameters meant to simulate operation of an FTR fuel element near the center of the core for its entire life. Subsequent capsules were to incorporate improvements in capsule design based on the performance of the first capsule and were intended to examine the performance of fuel pins with less conservative designs to establish the range of conditions for which mechanical interaction may be a real problem in LMFBR-type fuels.

4. DESCRIPTION OF EQUIPMENT

4.1 Mechanical Design and Instrumentation

The MINT-1 capsule¹⁰ incorporated several special features and instruments to provide simultaneous measurement of fuel column motion and differential motion between the cladding and the fuel. A schematic drawing, which reveals the general arrangement of the components, is shown in Fig. 1. The type 316 stainless-steel-clad fuel element, shown in detail in Fig. 2, was submerged in NaK, which served as a heat transfer medium. The NaK was contained in a type 304 stainless steel primary containment vessel. A small helium-filled gas gap was provided between the primary and the type 304 stainless steel secondary container. The secondary container was in contact with the ORR pool water, to which all thermal energy was transmitted.

The primary and secondary containers and the fuel pin were rigidly connected at the bottom. The upper end of the primary container was connected to a central bulkhead with a stainless steel bellows. This bellows allowed for relative expansion between the primary and secondary container tubes. To permit free movement of the cladding, the fuel pin was sealed to the central bulkhead with another stainless steel bellows, which was welded to a ferrule on the cladding. The ferrule, which also supported one of the motion detection units, was in turn brazed to the fuel pin cladding. This arrangement permitted free motion of the cladding.

ORNL-DWG 72-10097

Fig. 1. Conceptual Drawing of MINT-1 Capsule Lower Portion.

Fig. 2. MINT-1 Fuel Element.

Motion Transducers

Two variable-permeance differential transducers (VPDT's) were used to measure the movement of the fuel column and the cladding. The VPDT's measured movement by changes in inductive reactance caused by movement of a metal core within a field coil. The signal from the transducer coil was then transmitted to signal conditioning equipment that converted the output to a dc voltage signal. The relationship between core movement and output signal was established in calibration tests discussed in Appendix A.

The cores of the transducers were fastened to a spring-loaded train of rods that rested on the top of the fuel column, as revealed in Fig. 2. The motion of the fuel pellets was transmitted by the push rods to the transducer cores and detected by changes in output from the transducer coil circuit. The spring kept the push rod in contact with the top of the fuel column. The 2-lb preload placed on the spring simulated the static load resulting from the fuel column weight in a full-length FTR fuel element. The upper VPDT, which was fixed to the secondary container, detected fuel column movement. The lower VPDT, which was fastened to the ferrule on the cladding, measured differential movement between the fuel and the cladding. The lower end cap on the fuel pin had an integral rod that extended through and was welded to both primary and secondary containment vessels. This arrangement established a fixed reference point from which all motion could be measured. By subtraction of the motion of the lower transducer core from the motion of the upper transducer core, the axial movement of the cladding was determined, as described in more detail in Sect. 6.1.

Integral Calibration System

A solenoid-operated calibrating device was located just above the upper transducer. The solenoid coil surrounded the upper end of the fuel pin. The solenoid core was fixed to the upper end of the push rod assembly, inside the fuel pin. Actuating the magnet's winding lifted the push rod assembly against its spring to one of two fixed stops, thereby providing a means for *in situ* calibration of the VPDT's. The magnet core was connected to an internal cam, as shown in Fig. 3, that

Fig. 3. In-Test Calibration Assembly.

caused a 90° rotation on alternating strokes of the magnet core. The cam geometry and rotation enabled calibration at two different fixed elevations any time during irradiation. A special instrument package provided slow, controlled lifting and releasing of the push rod. This was necessary (1) to avoid excessive loads on the cam during lifting, (2) to prevent overheating of the solenoid, and (3) to prevent shock loading of the fuel during release of the push rod. The instrument was programmed to adjust (1) the ramp up to full magnet power, (2) the hold time at power, and (3) the ramp down in power. The instrument package has been described previously.¹¹

Gas Pressure Measurement System

A capillary tube extended from the top end closure of the fuel pin to a pressure transducer, located above an offset portion of the capsule. In this location the pressure transducer operated at a low constant temperature and away from any appreciable neutron flux, thus reducing the chances for irradiation-induced degradation. The pressure transducer consisted of a VPDT unit whose core was fastened to a bellows diaphragm, as shown in Fig. 4. Gas pressure changes caused deflection of the bellows diaphragm, which in turn moved the core relative to the transducer windings.

Thermocouples

Temperatures were monitored by 13 Chromel P vs Alumel thermocouples sheathed with 1/16-in.-OD type 304 stainless steel, insulated with MgO,

Fig. 4. Pressure Transducer.

and manufactured with insulated junctions. The six thermocouples that monitored the fuel region were brazed to the inside of the primary containment. We avoided attaching the thermocouples directly to the cladding, to minimize possibility of mechanical interference between the thermocouples and the fuel element. Since the thermocouples were immersed in the NaK annulus, cladding and fuel temperatures could be calculated from thermocouple measurements as described in Sects. 4.2 and 6. Seven other thermocouples were located in the region above the fuel to measure the temperatures of the instruments and indicate the cladding temperatures there.

Flux Monitoring Guide

An additional feature of the capsule was an external guide, running along the back side of the capsule, for flux monitoring wires to measure the flux profile along the capsule during test operation.

Complete details of the mechanical design of the capsule are available in Reactor Division drawing M-10571-RM-001 and its associated drawings, as listed in Appendix B.

4.2 Thermal Design

Thermal design for this experiment was based on near-term application for the FTR, with overall application to the Liquid-Metal Fast Breeder Reactor (LMFBR). The capsule was designed to operate at steady-state heat ratings up to 19.5 kW/ft and to burnups up to 10% FIMA with daily

power cycles. The standard heat-up time to power was set at about 2 to 3 hr to simulate reactor startup. To simulate reactor scrams the capsule was cooled down rapidly by continuously retracting it from the reactor face at a rate of about 7 in./min. This cooled the fuel from operating to minimum temperature in less than 1.5 min.

The operating sequence for the MINT-1 capsule called for operation at 17 kW/ft with occasional overpower cycles to 19.5 kW/ft. Operation at 17 kW/ft was chosen to match the fuel center-line temperature expected in the hottest channel of the FTR. This matching is illustrated in Fig. 5, where selected temperatures for the MINT capsule design are compared with those for the peak FTR fuel pin. An earlier analysis¹² showed that prototypic LMFBR fuel temperature distributions can be obtained in a thermal flux environment.

Design heat transfer calculations were made with the one-dimensional GENGTC code¹³ and the two-dimensional HEATING3 code.¹⁴ The results of the fuel specimen midplane temperature calculations are summarized in Fig. 6 for various heat generation rates. Complete results from the HEATING3 calculations are given in Appendix C. The calculation included fission heat plus 0.5 W/g gamma heat in all materials. After the design of MINT-1, experimental results on other capsules similarly located in the ORR have shown¹⁵ that the gamma heat was about 1.5 W/g. Since the gamma heat is insignificant compared to fission heat from the fuel, the basic thermal design for the capsule was well within desired limits. However, the high gamma heating caused the VPDT region temperatures to be higher than predicted, and some remedial modifications to the capsule were required.

The peak heat flux to the pool water in the vicinity of the fuel specimen was $340,000 \text{ Btu hr}^{-1}\text{ft}^{-2}$ at 16 kW/ft, $400,000 \text{ Btu hr}^{-1}\text{ft}^{-2}$ at 19 kW/ft, and $435,000 \text{ Btu hr}^{-1}\text{ft}^{-2}$ at the maximum permitted level of 20.6 kW/ft. These heat fluxes result in subcooled nucleate boiling at the capsule surfaces but are well below a conservative estimate of burnout heat flux at $600,000 \text{ Btu hr}^{-1}\text{ft}^{-2}$.

5. SPECIAL FABRICATION

5.1 Fuel Element

The fuel element in this capsule had both internal and external instrumentation components as well as the standard fuel column. The cutaway isometric view shown in Fig. 2 reveals the essential features of the element.

Fuel Material

The cold pressed and sintered (U-25% Pu)O₂ pellets were procured from Pacific Northwest Laboratories in accordance with prototypic FTR Fuel Product Specification A-0117A (Oct. 27, 1969) and Process Specification A-0097 (May 26, 1969) with a minor exception necessary for lower density. At ORNL¹⁶ the pellets were heat treated as follows to reduce absorbed gases and adjust the oxygen-to-metal ratio to 1.95:

1. heated to 1450°C at a rate of 300°C/hr with an Ar-4% H₂ purge gas at a flow rate of 2.5 scfh;
2. held 42 hr at 1450°C until the H₂O content of the purge gas was below 30 ppm;
3. cooled to 850°C and gas changed to argon; and
4. cooled to room temperature.

The characterization of the fuel as received and after heat treatment is given in detail in Appendix D.

As shown in Fig. 7, the fuel contained some large inclusions. These inclusions usually had a bright metallic appearance immediately after polishing but quickly became gray. In this picture some of the metallic luster has been retained. Electron microprobe analysis indicated that such inclusions were rich in iron. Wet chemical analysis of the pellets confirmed the presence of iron as a significant tramp element. The origin of this impurity is probably from iron-base alloy materials used in production of the powder or the fuel pellets.

In addition, microscopic examination also revealed the presence of a second-phase gray material uniformly distributed throughout the fuel pellets (see center of Fig. 8). Electron microprobe analysis showed these

Fig. 7. Microstructure of (U,Pu)O₂ Pellet Containing a Large Inclusion. 200x.

Fig. 8. Typical Microstructure of (U,Pu)O₂ Pellet Used in MINT-1 (without inclusion). 500x.

areas to be rich in plutonium compared to the matrix. These areas are probably rich in Pu_2O_3 . Supporting information for this conclusion can be found in data by Chung et al.¹⁷

The insulators at the ends of the fuel column were 0.1939-in.-diam solid 91%-dense ThO_2 pellets. There was 0.453 in. of insulator above the fuel and 0.220 in. below.

Cladding

The cladding for the MINT-1 fuel pin was 20%-cold-worked type 316 stainless steel purchased from Carpenter Steel Company to Specification B-58992, Rev. 1 as prototype FFTF tubing. The tubing was lot MR-83627 from heat V87210. The ORNL record identification number was MAT-48-2-C. ORNL inspections included measurement of outside and inside diameters and wall thickness and a search for wall defects. The tubing was free of flaws giving an ultrasonic indication greater than that from a notch 0.001 in. deep $\times$ 0.030 in. long. The outside diameter was 0.2300 ± 0.0001 in., the inside diameter was 0.1988 ± 0.0003 in., and the wall thickness was 0.0165 ± 0.0007 in.

Fuel Element Assembly

The following assembly procedure was used in fabricating the fuel element:

1. braze lower transducer support bulkhead to the cladding;
2. attach fixed solenoid core, nonmagnetic spacer, and pressure transducer tubing to upper end cap;
3. weld upper end cap assembly to cladding and perform a leak check;
4. assemble push rod unit with transducer cores, spring, spring retainer, solenoid core, and calibrated stepping cam;
5. insert push rod assembly into cladding and swage the spring retainer in place;
6. insert 2 top insulator pellets, 43 fuel pellets, and 1 bottom insulator pellet;
7. attach lower end cap by welding followed by final leak check; and
8. fill the fuel element with 1 atm of high-purity helium.

5.2 Capsule Brazeents

The assembly of the primary containment of the capsule required the use of two brazed subassemblies. The bulkhead support brazement consisted of a machined fitting about 1 in. in diameter $\times$ 1 in. long. Two 1/8-in.-diam tubes and a 1/16-in.-diam sheathed thermocouple penetrated the bulkhead and were held in place and sealed by brazing. It was essential that braze metal fillets be complete but that no braze alloy be allowed on nearby surfaces that would subsequently be welded. This was accomplished by carefully placing precise amounts of braze alloy compound at the joints and by closely surrounding the alloy with a stop-off material to avoid running of the alloy during brazing. The procedure for making this assembly is described in MET-FCT-PP-42 in Appendix E.

A second more complicated brazement was used for placement of thermocouples inside the primary containment vessel. Six 1/16-in.-diam sheathed thermocouples penetrated a bulkhead at the bottom of the vessel and were brazed to the inside wall at precise locations. The braze alloy was applied to the thermocouples by plating with a layer of nickel-phosphorus alloy followed by a layer of chromium to achieve a bulk composition like that of Microbraz 50. The penetrations were sealed by brazing with Microbraz 50. The procedures for making this assembly are presented in MET-FCT-PP-38 in Appendix F.

6. DATA

6.1 Operating Data

The data presented consist of fuel column and cladding length changes, internal fuel element pressures, and cladding temperatures. These data are shown in Fig. 9 and 10 as functions of operating date. The fuel column length change (expansion) was determined by subtracting the fuel column length indicated at zero power on November 22, 1971, from the length measured at any given time. Therefore, positive values reflect growth, and negative values reflect shrinkage. Cladding length change was determined by subtracting the length change recorded by the

Fig 9. MINT-1 Operating History. (a) Startup through cycle 6.

Fig. 9(b). MINT-1 cycles 7 through 20.

Fig. 9(c). MINT-1 cycles 20 through 27.

Fig. 9(d). MINT-1 cycle 28 through end of experiment.

Fig. 10. Cladding Expansion and Temperature History.

differential transducer (which measures the difference between the fuel column movement and the cladding movement) from that measured by the fuel column transducer. This is described by the following equations:

$$XU \text{ (upper transducer reading)} = DF ,$$

$$XL \text{ (lower transducer reading)} = DF - DC ,$$

where

DF = fuel column length change, and

DC = cladding length change.

$$XU - XL = DF - (DF - DC) ,$$

$$XU - XL = DC .$$

The internal pressure (P) was obtained by assuming that atmospheric pressure existed at zero power on November 22, 1971, and adjusting the

calibration equation accordingly to obtain 0 psig at the output voltage (/) recorded on this date. The adjusted polynomial equation determined by a least-squares fit to the calibration data is:

$$P \text{ (psig)} = 0.950426V^2 - 40.224V - 26.133 .$$

The cladding temperature at each thermocouple location along the fuel element was determined from thermocouple readings and corrections based on the relationship between thermocouple and cladding temperatures derived from the thermal analysis presented in Appendix C. The equation is described below:

$$T = -8.95 + 1.21(TE) + 3.15 \times 10^{-4}(TE)^2 - 7.87 \times 10^{-8}(TE)^3 ,$$

where

TE = thermocouple temperature, °C, and

T = average temperature at the outer wall of the cladding, °C.

The average surface temperature along the fuel element cladding was then calculated with a modified Simpson's rule approach described in Appendix G. This method of characterizing the thermal condition of the cladding was considered to be more representative than a simple averaging of the three pairs of thermocouples, since the axial temperature distribution is approximately parabolic.

The midplane heat rating plotted in Fig. 9 was determined by averaging the midplane thermocouples and using the HEATING3 curve shown in Fig. 6, p. 9, for estimating heat rating from calculated thermocouple temperatures.

6.2 Neutron Radiography

Neutron radiography was used to verify the proper assembly of the test, to check the final indications of the transducers, and to examine the effects of irradiation exposure on the capsule.

The fact that the fuel column did shrink as measured by the fuel transducer was confirmed by pre- and post-irradiation neutron radiographs

that showed fuel column shortening of about 0.065 ± 0.005 in. This compares very well with the maximum movement of 0.061 in. measured by the transducers.

Neutron radiographs of the fuel column also revealed bowing of the fuel element and the expected rearrangement of the fuel. The pre- and post-test position of the fuel element with respect to the primary container is shown in Fig. 11.

The restructuring of the fuel was characterized by a low-density region in the center, indicating a central void that terminated in the end pellets. At the upper end of the fuel column, the neutron radiograph indicated that the lower portion of the ThO_2 insulator pellet adjacent to the top $(\text{U,Pu})\text{O}_2$ pellet had mixed with the fuel. This attested to the relatively high temperatures apparently caused by flux peaking at the top of the fuel column.

The neutron radiographs also indicated that there was no significant change in the length of the cladding.

Fig. 11. Schematic of Fuel Element Position in Primary Container Before and After Test Exposure.

7. INSTRUMENTATION PROBLEMS

Several difficulties were encountered with the instrumentation of the MINT-1 capsule. Such problems are not unusual with the first model of a new capsule design.

7.1 Calibration Solenoid Operation

The system for in-test calibration of the position transducers operated successfully through 30 test calibration cycles during final assembly and check-out of the capsule. Unfortunately, the system failed by an apparent short in the solenoid magnet winding after the 30th cycle. This failure was not expected since similar units had operated through as many as 300 cycles during development of the system. The failure occurred after capsule assembly was complete and just before scheduled reactor insertion. Since the calibration of the position transducer could be verified at the beginning and end of the test by neutron radiography, and repair of the solenoid magnet would have been costly and time consuming, we inserted the capsule with the inoperable calibration system.

7.2 Motion Transducer Temperature

During the MINT-1 startup period (September 1971 through March 1972) we ascertained by resistance measurements that the coil temperatures of the motion transducers were not being adequately represented by the thermocouples attached to the transducer casing. Through collection of data at various heat ratings and during several reactor fuel loadings, we were able to correlate coil temperatures as measured from resistance values with thermocouple-measured temperatures. These relationships were also established later in the test after installation of external stainless steel and lead gamma shields. The purpose of the shields was to reduce the heating of the transducer coils. All of these correlations are presented in Appendix H.

Calibration tests were done with a heated transducer identical to those used in the capsule to investigate the effect of temperature and thermal gradients on transducer behavior. From these tests we established an empirical correlation of transducer core position with voltage output,

coil temperature, and axial thermal gradient. These results are summarized in Appendix A.

The correlations described above were used in determining the position of the transducer cores throughout the operation of the MINT-1 capsule. Reasonable agreement was obtained between the position derived with these correlations and that observed by neutron radiography at the end of the test (see Sect. 6.2).

7.3 Motion Transducer Failures

Both the motion transducers in the MINT-1 capsule ultimately failed and caused termination of the irradiation. Both, however, worked long enough to provide useful data, and, since the failures were probably due to the above mentioned overheating, this type of transducer is probably basically satisfactory for a capsule of this type if provided with better cooling.

The lower transducer, which measures the differential movement between the fuel column and cladding, failed when a short circuit developed after about 400 hr of operation with only 5 hr of capsule operation above 10 kW/ft. While loss of the lower transducer degraded data collection somewhat, the goal of the experiment to measure fuel stack height changes and subsequent indications of mechanical interaction could still be achieved so long as the upper transducer functioned.

The upper transducer became inoperative after about 2500 hr of operation as evidenced by a large negative voltage shift on the instrument readout. Subsequent measurements revealed a high resistance in the lower coil circuit inside the capsule. It is difficult to ascribe a cause to this problem. Among the possibilities are:

1. a partially broken wire,
2. a faulty joint or connection, or
3. a necked-down section in the wiring.

The failure was probably accelerated by the rapid thermal cycling that resulted from the power transients that were part of the program as well as occasional reactor scrams. We were also operating the transducers at the upper temperature limit (230 to 250°C) recommended by the

manufacturer. However, the only effect of overheating the transducers was expected to be a deviation from their calibration curve, rather than failure.

The capsule was operated for 12.5 days after the loss of the second transducer to further study the pressure changes occurring inside the fuel element.

7.4 Irregular Motion Indications

During cyclic operation of the experiment it became apparent from irregular indications by the motion transducers that either the upper fuel pellets or the push rod, which connects the transducer cores to the top of the fuel column, was sticking during contraction of the fuel column. The phenomenon was evidenced in three ways. First, the data taken at zero power after each initial operation at a new high power level above 10 kW/ft were irregular. As an example, while operating at 13 kW/ft during cycle 7 the fuel column transducer showed no contraction. Upon subsequent reduction to zero power this transducer indicated that the column had contracted about 15 mils with respect to its position before cycle 7. This same type of behavior was noted for cycles 8 and 26. The interpretation is that the fuel column must have been shrinking at power, but the push rod did not follow until mechanical movement (vibration) during capsule retraction caused its release. Additional evidence of this phenomenon was found during heat-up for some of the power cycles. As an example, just before heat-up for cycle 10 the indicated fuel column position was about -42 mils (compared to the start-of-test position) at zero power. During the early part of heat-up for cycle 10, an abrupt change occurred to -53 mils, reflecting release of the push rod. Finally, instantaneous downward movements of the push rod at irregular intervals was observed during continuous retraction of the experiment. The retraction data for cycle 8 shown in Fig. 12 is an example of such behavior.

The formation of gaps between pellets has been observed during cycling of pellet-filled fuel pins in-reactor.^{4,18} The formation and closure of such gaps during power cycling in the MINT-1 capsule would

Fig. 12. Fuel Column Transducer Record During Retraction at End of Cycle 8.

explain the preceding observations. The bond between fuel and cladding that results in such unstable gaps between pellets will not sustain appreciable loads and, therefore, would not constitute significant mechanical interaction. The alternate explanation of such behavior, sticking or seizing of the push rod within the cladding above the fuel column, would be aggravated by the observed bowing of the fuel pin and cannot be eliminated as a possibility.

7.5 Flux Monitor Experience

One attempt was made to measure the axial flux distribution using stainless steel flux monitor wires. The flux profiles constructed from the data were not reasonable within themselves or by comparison to other flux profile data from the ORR. Insufficient time and funds precluded further experiments to delineate the axial flux distribution.

The flux profile used in the analysis of this experiment was obtained from previous experience with the facility and is described in Appendix I.

8. DISCUSSION OF RESULTS

The data collected during the operation of the MINT-1 capsule will be discussed with respect to internal pressure buildup within the fuel pin, fuel column behavior, cladding behavior, and mechanical interaction. As may be expected for the first capsule of a new design, a significant amount of time was employed during the test period to evaluate and adjust the instrumentation. This work accounts for the absence of data from several time periods during the test.

8.1 Internal Gas Pressure

The sparsity of pressure data collected during startup [see Fig. 9(a), p. 14] limits the conclusions that can be drawn about the initial pressure rise due to adsorbed gases released within the fuel pin. However, the data collected during first operation at 4 kW/ft (cycle 2) clearly show that the pressure rise caused by adsorbed gases had reached a maximum and was decreasing with time. At 4 kW/ft the fuel temperatures exceeded 400°C according to the calculations presented in Fig. 6, p. 9. This should be sufficient to liberate most of the adsorbed gases. The observed decrease in pressure was presumably caused by loss of gas due to reaction and diffusion from the fuel pin. Such behavior is consistent with the results of earlier work,¹⁹⁻²² which showed no appreciable contribution of initially contained gases to the total pressure within operating fuel pins. Later operation of MINT-1 (cycles 4-6) at intermediate heat ratings and somewhat higher fuel temperatures caused very little pressure rise, thus confirming the conclusion that most of the adsorbed species were removed during operation at 4 kW/ft. The slightly negative pressure values reported during this period of operation resulted from the arbitrary base line of zero pressure assumed at zero power on November 22, 1971. It is quite likely that the temperature of the pool water (approx 45°C) even at zero power before initial startup was sufficient to cause release of some of the adsorbed gases and therefore cause the pressure to be slightly greater than atmospheric pressure.

Of perhaps more interest is the pressure imparted by release of fission gases at higher power and during power cycling. During the first long-term operation of greater than 13 kW/ft (cycle 8) the pressure data clearly show that fission gas release was a continuous function of time at operating power. Furthermore, very little gas release was associated with the thermal transient in going from operating power level down to zero and back to operating power. This continuous release was obtained throughout the test, including the long cycle 31, and was consistent with results from some tests^{20,23-25} but contrary to those found in others, in which fission gas release was noted essentially only during the power transient.^{19,21,22} There are numerous differences between these tests and the reasons for the disparities are not completely clear. In the earlier tests, which showed a marked effect of power cycling on gas release, the effect was attributed to fuel cracking during the cycle. Our results on gas release and fuel column expansion (Sect. 8.2) may indicate that this FTR fuel under these power transient conditions is less subject to thermal shock cracking than were the fuels in previous tests. If this indication is correct, it would explain the lack of crack-induced effects on gas release, whether cracks cause true gas release or, as seems reasonable, merely change the distribution and temperature of gas within the fuel pin. (Cracks created during shutdown may cause an increase in the average temperature of gas space within the fuel region of the fuel pin by admitting gas to the hotter interior of the fuel. In pins with small ratios of plenum volume to total void volume, this could cause an apparent pressure increase during or after shutdown. These cracks would anneal out during operation at power, masking continuous gas release by lowering the average gas temperature. Such a model would explain the apparent observation of release only at shutdown in tests with small plenum volumes^{19,21,22} and continuous release in other tests with large plenum volumes. This type of explanation is consistent with Nottley's²⁶ presentation of crack behavior and potential error estimates.)

The rate of gas release also increased with increasing operating power level, as seen by the rate of pressure rise. The steady-state gas release (atoms released per atom generated) calculated from the observed pressure at three stages of operation is presented in Table 1. From

Table 1. Fission Gas Release

Operation Period (cycle)	Midplane Heat Rating (kW/ft)	Gas Release	
		(std cm ³ /hr)	(%) ^a
13	13.5	0.0044	30
25	14	0.0055	36
31	17	0.0228	126

^aThe percentage release is based on the midplane burnup rate.

these data it is apparent that, as new high heat ratings and fuel temperatures are achieved, the gas release fraction is a function of both power level and operating history. The 126% release rate evidenced at 17 kW/ft over a 12-day period is consistent with an increased true steady-state release rate combined with incremental release from fuel undergoing restructuring at the new high temperatures. Such restructuring has been observed²⁷ to continue for periods of greater than 28 days, and enhanced release has been attributed to this cause by Hurme.²¹ Upon completion of this restructuring, the release rate would be expected to decrease to the true steady-state release value for this power level. Termination of the test, which was not operated with this type of measurement as a principal objective, prevented determination of the true steady-state release fractions as a function of power level and state of fuel restructuring.

The total amount of fission gas released in our experiments was calculated from the pressure measurements to be approximately 56% after 1.7% FIMA at the end of test. (The calculation methods are presented in Appendix I.) This observation is consistent with the preponderance of published data^{28,29} on similar fuels at this burnup level.

8.2 Fuel Column Length

The data on fuel column length have been examined for information on in-reactor contraction and expansion of the column during constant power

operation and for the effects of irradiation-induced changes on the measured thermal expansion of the fuel column.

The data used to analyze the effects of operation at constant power were taken from the measurements of fuel column height at zero power. These data, which reflect the effects of changes in fuel length at power, are somewhat erratic. Such irregularity is not uncommon in tests of this type.^{4,30} The data fall into two groups — those points where the fuel column contracted to a continuous stack of pellets and those points where gaps existed in the pellet stack (or the push rod seized) preventing the determination of true fuel length at low power. If the zero-power and at-power data are examined together the zero power data can be readily separated into these two groups. The zero power data after the beginning of cycle 2 until the end of 7 are too high, as are those from the beginning of cycle 17 to the end of 21, after the start of 23 to the end of 25, and after the start of 27.

Contraction at Power

Examination of the data presented in Fig. 9 (p. 14) reveals that the fuel column height, as measured at zero power, decreased markedly on three occasions. These occasions (cycles 7, 8, and 26) corresponded to the first period of operation at any given power level above 10 kW/ft. The contractions are listed in Table 2. Such contractions have been observed in most tests of this type.^{18,30-35} In the present case they were observed when the fuel surface temperature first reached about 650°C and the inner edge of the land or dish in the fuel reached about 1000°C. These temperatures compare well with the plasticity temperatures of 750 to 1000°C reported previously.¹ The contractions in the present experiment were apparently greatly slowed or complete after 60 to 70 hr at 10 to 16 kW/ft. In an experiment^{2,33} with UO₂ fuel operating at about 16 kW/ft the contractions lasted about 10 hr. In contrast, in an experiment¹⁸ operated at about 5 kW/ft the contractions lasted about 1.5 months, even though the points of contact between the flat-ended UO₂ pellets were initially at about 1450°C. This comparison suggests that temperature-gradient-induced stresses may accelerate the contraction of the fuel in fuel elements at a high power rating.

Table 2. MINT-1 Fuel Column Contraction

Cycle	Operating Power (kW/ft)	Time at Power (hr)	Fuel Contraction (%)
7	10-13	57	0.15
8	13-15.5	72	0.47
26	16.3	72	0.13

Growth at Constant Power

The zero-power fuel column length data from the MINT-1 capsule show two periods when fuel stack height increased or expansion occurred with time or burnup at relatively constant power. The data from these two periods are tabulated in Table 3.

The expansion measured in this test may be compared with that measured in an earlier test¹⁸ that contained UO_2 fuel operated at much lower power with lower fuel temperatures (1450°C central). The time rate of fuel expansion was much slower ($0.1 \times 10^{-6}/\text{hr}$) for the earlier test, and the burnup-based rate was also slower ($0.6 \times 10^{-22} \text{ fission}^{-1} \text{ g}^{-1}$) but was closer to our results.

In neither of these tests was the axial fuel swelling rate as high as the $2 \times 10^{-22} \text{ fission}^{-1} \text{ g}^{-1}$ that would be predicted on the basis of uniform solid fission product swelling by the analysis of Olsen et al.³⁶ This probably reflects the accommodation of some of the fission-product-induced swelling in preexisting voids within the fuel and the reduction of swelling by release of fission gas.

Table 3. MINT-1 Fuel Column Growth

Cycles	Operating Power (kW/ft)	Time at Power (hr)	Fuel Expansion (%)	Rate	
				(hr^{-1})	($\text{fission}^{-1} \text{ g}^{-1}$)
				$\times 10^{-6}$	$\times 10^{-22}$
9-16	13.5	190	0.07	3.7	1.3
22-25	13.8-14.4	288	0.08	2.8	1.0

Thermal Expansion

The data presented in Fig. 9 may be examined for the determination of fuel thermal expansion after the effects of fuel column contraction and expansion at power are eliminated. The results of such an examination are presented in Fig. 13, where all of this type of data from the MINT-1 test are plotted. The points represent the expansion of the fuel column during each power change. The two curves are the expansions predicted from the temperatures calculated in one case for the fuel surface and in the other case for the inner edge of the dish in the ends of the fuel pellets. A thermal expansion coefficient³⁷ of $10 \times 10^{-6}/^{\circ}\text{C}$ was used. These results indicate that the thermal expansion of the fuel was controlled by a temperature between the two used for the calculations. This finding is consistent with results of earlier tests.^{1-4, 30, 31} The set of points below the lower curve at around 14 kW/ft indicates that the calculated average fuel surface temperatures may have been about 50°C too high because of uncertainty in the fuel-to-cladding gap conductance. The scatter in the data may be due to the changes in the length of cracks in the fuel from cycle to cycle.

8.3 Cladding Behavior

The results regarding cladding behavior are limited to the startup period of operation since the differential transducer, which enabled us to measure cladding expansion, became inoperative (as described in Sect. 6). The cladding results are presented in Fig. 10. The behavior of the cladding is compared in Table 4 with that expected from calculations of the expansion. The predicted values are based on average cladding temperature changes calculated by the method described in Sect. 6. A value of $17 \times 10^{-6}/^{\circ}\text{C}$ was used as the expansion coefficient. No corrections were made for expansion of the capsule and measurement train since the design of the equipment brought about cancelling expansions that would amount to less than 5 mils error over the entire operating range. The comparisons at about 2, 4, and 6 kW/ft operating levels show a disparity of 12 to 15 mils between actual and predicted values. This is larger than expected, even considering the neglected

Fig. 13. Thermal Expansion of (U,Pu)O₂ Fuel Column in MINT-1 Experiment. Open circles indicate measurements for which reference to true zero expansion was possible.

Table 4. Comparison of Measured and Predicted Cladding Expansion

Cycle	Midplane Heat Rating (kW/ft)	Average Cladding Temperature Change ^a (°C)	Cladding Expansion, mils	
			Predicted ^a	Measured
1	1.8	140	23	11
2	3.8	200	33	18
4	6.0	230	37	24
6	7.6	270	44	38
6	9.8	315	51	47

^aBased on 9.6-in. cladding length, measured cladding temperatures, and an expansion coefficient for type 316 stainless steel of $17 \times 10^{-6}/^{\circ}\text{C}$.

error in the measurement train expansion and the error involved in estimation of average cladding temperature. The source of a large portion of this difference became obvious at the beginning of cycle 6, when the strip-chart records revealed an instantaneous and significant apparent upward movement of the fuel column and a simultaneous but insignificant small

change in the differential movement recorded by the lower transducer. The fuel column transducer coil body was apparently loosely stuck to the cladding and had been partially moving with it, thereby reducing the amount of movement indicated by the core. When the coil body released from the cladding it sprung downward about 7 mils into a free position. From this time until the lower transducer failed (about 30 hr), the comparison between actual and predicted values was quite good, as shown in Table 4 for cycle 6. In Fig. 10, it is also apparent from the zero values at zero power level that the cladding showed no permanent expansion or contraction during this period of operation. This observation was verified by the postirradiation neutron radiographs (see Sect. 6.2 of this report).

8.4. Mechanical Interaction

No evidence of significant mechanical interaction was seen during this test. This conclusion is based principally on the lack of cladding deformation. Supporting evidence is found in the uniformity of the fuel column expansion data obtained during heat-up throughout the test. A plot of typical expansion versus heat rating data for various cycles is presented in Fig. 14. It is quite apparent that the expansion of the column increased steadily with increasing heat rating during all of these cycles. If mechanical interaction had occurred, the rate of expansion might have decreased at the onset of interaction because of restraint by the cladding. Such behavior has been observed by others where mechanical interaction has occurred.^{2,4,31} The lack of significant mechanical interaction in this test is not surprising since the fuel element design incorporated a generous fuel-cladding gap, and the final burnup was too low to cause gap closure.

9. CONCLUSIONS AND RECOMMENDATIONS

The operation of this test provided useful insight into gas release behavior for FTR prototype fuel and confirmed the low-burnup expansion behavior expected for dished fuel pellets. In addition, it was instructive

ORNL-DWG 72-10104

Fig. 14. Fuel Expansion During Heat-Up.

in identifying some problems in the design and apparatus. The specific conclusions and recommendations are itemized below.

1. No evidence of significant mechanical interaction was found.
2. All of the observed cladding length changes were due to thermal expansion.
3. The fuel column expansion during power transients was controlled by temperature changes in the outer one-seventh of the FTR dished pellet.
4. Axial fuel pellet shrinkage occurred each time the fuel pin was operated at any *new high* power level above 10 kW/ft, probably because of irradiation-enhanced creep, sintering, or both in the fuel. This phenomenon appears to be accelerated by operation at higher fuel linear heat ratings.
5. The fuel column expanded slightly during constant power operation, probably because of accumulation of fission products.

6. The net fuel column length change after operating 15,783 kWhr to a burnup of 1.7% FIMA at power levels from 10 to 17 kW/ft was a shrinkage of 61 mils (0.64%) for the 9.6-in.-long fuel column.

7. Fission gas release for prototypic FTR fuel was continuous with respect to time at power and did not depend significantly upon power cycling.

8. The fission gas release rate increased with increasing operating power level. At 13.5 and 14 kW/ft the estimated steady-state releases at low burnup were 30 and 36%, respectively. The total gas release after 1.7% FIMA with an end-of-life heat rating of 16.6 kW/ft was 56%.

9. Most of the adsorbed gases were released from the fuel at low power (approx 4 kW/ft) and quickly reacted and/or diffused out, thus having an inconsequential effect upon internal gas pressure.

10. Future capsule designs incorporating VPDT's should provide for their operation in cold regions to avoid effects of thermal gradients and minimize chance of damage by thermal cycling.

11. Future capsule designs should provide better centering of the fuel elements and sufficient supports to prevent bowing of the element.

ACKNOWLEDGMENTS

We would like to gratefully acknowledge the very important contributions made to the operation of this experiment by J. W. Cunningham and R. L. Shepard, of the ORNL Instruments and Controls Division, and J. M. Googe, of the University of Tennessee Electrical Engineering Department.

REFERENCES

1. M.J.F. Notley and A. Harvey, *The Length Changes of Zircaloy-Sheathed UO₂ Fuel Elements During Irradiation*, AECL-1346 (CRFD-1174) (August 1963).
2. G. Kiaerheim and E. Rolstad, "In-Core Study of the Mechanical Interaction Between Fuel and Cladding," *Nucl. Appl. Technol.* 7: 347-60 (October 1969).
3. J. F. Giovenjo, *In-Pile Dimensional Changes of ThO₂-UO₂ Fuel Rods with Non-Free-Standing Cladding (LWBR Development Program)*, WAPD-TM-986 (November 1970).
4. D. A. Cantley et al., *Axial Expansion of Mixed-Oxide Fuel Measured In-Pile*, GEAP-10403 (July 1971).
5. E. Rolstad and K. D. Knudsen, "Studies of Fuel-Clad Mechanical Interaction and the Resulting Interaction Failure Mechanism," *Nucl. Technol.* 13: 168-76 (February 1972).
6. S. A. Rabin et al., "Mixed Oxide Fuel Movement at Various Power Levels and in Transients," pp. 524-33 in *Proceedings of Conference on Safety, Fuels, and Core Design in Large Fast Power Reactors*, ANL-7170 (1965).
7. F. J. Homan, *A Parametric Analysis of Fuel-Cladding Mechanical Interactions*, ORNL-TM-3508 (August 1971).
8. J. H. Gittus, *Theoretical Analysis of Some Forces, Stresses, and Strains Produced in Nuclear Fuel Element Cladding by Thermal Expansion of Cracked Fuel Pellets*, TRG-Report-1547 (August 23, 1967).
9. D. B. Trauger, *Some Major Fuel-Irradiation Test Facilities of the Oak Ridge National Laboratory*, ORNL-3574 (April 1964).
10. R. L. Senn, J. A. Conlin, and R. B. Fitts, "An Improved Capsule Design for Experimental Measurement of Fuel-Cladding Mechanical Interaction" (Summary) *Trans. Amer. Nucl. Soc.* 15(1): 218-19 (June 1972).
11. J. L. Redford, "Current Profile Programmer," *Instrumentation and Controls Div. Annu. Progr. Rept. Sept. 1, 1971*, ORNL-4734, pp. 60-61.
12. A. R. Olsen, R. B. Fitts, and C. M. Cox, "Analysis of the Validity of Fast Reactor Fuel Tests in Existing Test Reactors," pp. 127-50 in *National Symposium on Developments in Irradiation Testing Technology, Sandusky, Ohio, Sept. 9-11, 1969*, CONF-690910.

13. H. C. Roland, *GENGTC, A One-Dimensional CEIR Computer Program for Capsule Temperature Calculations in Cylindrical Geometry*, ORNL-TM-1942 (December 1967).
14. W. D. Turner and M. Siman-Tov, *HEATING3: An IBM 360 Heat Conduction Program*, ORNL-TM-3208 (February 1971).
15. B. Fleisher, K. R. Thoms, T. N. Washburn, and V. J. Tennary, "Operation of Capsules," *Fuels and Materials Development Program Quart. Progr. Rept. Dec. 31, 1971*, ORNL-TM-3703, pp. 238-39.
16. R. A. Bradley, "Mechanical Interaction Test Fuel Pin," *Fuels and Materials Development Program Quart. Progr. Rept. Mar. 31, 1971*, ORNL-TM-3416, pp. 7-8.
17. J. Y. Chung et al., "Oxide Fuel Characterization," Sect. 12 in *Oxide Fuel Element Development Quart. Progr. Rept. June 30, 1970*, WARD-4135-11.
18. S. C. Weaver, V. A. DeCarlo, R. B. Fitts, R. L. Senn, K. R. Thoms, and J. L. Scott, *Results from Irradiation Testing of UO₂ Fuel Pin Designed for the Medium Power Reactor Experiment*, ORNL-TM-2859 (August 1970).
19. T. B. Burley and M. D. Freshley, "Internal Gas Pressure Behavior in Mixed-Oxide Fuel Rods During Irradiation," *Nucl. Appl. Technol.* 9: 233-41 (August 1970); also BNWL-SA-2635.
20. M. B. Reynolds, "Measurement of Free Fission-Gas Pressure in Operating UO₂-Filled Fuel Rods," *Nucl. Sci. Eng.* 20(4): 386-91 (1964); also GEAP-4135 (Jan. 23, 1963).
21. M. Hurme, *Observations of Fuel Pin Internal Pressure*, HPR-110 (June 1969).
22. M. J. Notley, R. DesHaies, and J. R. MacEwan, "The Fission-Product Gas Pressures in UO₂ Fuel Elements During Irradiation," *Trans. Amer. Nucl. Soc.* 8(2): 424-25 (1965); also AECL-2662 (November 1966).
23. A. W. Longest, R. B. Fitts, and J. A. Conlin, "Fission-Gas Release Behavior in a Vented (U,Pu)O₂ GCFBR Fuel Pin," (Summary) *Trans. Amer. Nucl. Soc.* 15(1): 197-98 (1972).
24. R. M. Carroll, "Fission Gas Release During Fissioning in UO₂" (Summary) *Trans. Amer. Nucl. Soc.* 8(1): 22 (1965).
25. F. R. McQuilkin, V. A. DeCarlo, and R. L. Senn, "Fuel Capsule Irradiations in ORR Poolside Facility," *GCR Program Quart. Progr. Rept. Mar. 31, 1962*, ORNL-3302, pp. 57-61.

26. M.J.F. Notley, "Calculation of Fission-Product Gas Pressures in Operating UO_2 Fuel Elements," *Nucl. Appl.* 3: 334-42 (June 1967).
27. A. R. Olsen, R. B. Fitts, and W. J. Lachey, *In-Reactor Restructuring Temperatures and Kinetics for $(\text{U,Pu})\text{O}_2$* , ORNL-TM-3387 (July 1971); also pp. 579-602 in *Proc. Conf. Fast Reactor Fuel Element Technology*, American Nuclear Society, Hinsdale, Ill., 1971.
28. C. M. Cox, "The Irradiation Performance of Uranium-Plutonium Oxide Fuel Pins," *Nucl. Safety* 10(5): 380-91 (1969).
29. J.D.B. Lambert et al., "Performance of Mixed Oxide Fuel Elements - ANL Experience," pp. 517-54 in *Proc. Conf. Fast Reactor Fuel Element Technology*, American Nuclear Society, Hinsdale, Ill., 1971.
30. A. C. Bini et al., "In-Pile Direct Measurements of Fuel Axial Variation in Fast Reactor Pins," pp. 520-37 in *Fast Reactor Fuel and Fuel Elements*, (Proc. Int. Conf. Kernforschungszentrum Karlsruhe, Germany, Sept. 28-30, 1970), ed. by M. D. Donne, K. Kummerer, and K. Schroeter, Gesellschaft für Kernforschung mbH., Karlsruhe, Germany.
31. C. Hueber et al., "In-Pile Length Changes of ZrCu-Sheathed UO_2 Fuel Rods," (Summary) *Trans. Amer. Nucl. Soc.* 13(1): 138-39 (1970).
32. W. E. Baily, *Relative Thermal Expansion of UO_2 Fuel Inpile*, CVNA-152 (June 1962).
33. G. Kjaerheim and E. Rolstad, *In-Core Study of Fuel/Clad Interaction and Fuel Centre Temperature*, HPR-107 (January 1969).
34. G. Testa et al., "In-Pile Fuel Studies for Design Purposes," *Nucl. Appl. Technol.* 7: 550-60 (December 1969).
35. C. N. Spalaris, "Uranium Dioxide-Cladding Interactions. Axial Expansion of UO_2 Column in Fuel Elements," *Nucl. Sci. Eng.* 17: 381-91 (1963).
36. A. R. Olsen, D. A. Douglas, Y. Hirose, J. L. Scott, and J. W. Ullman, "Properties and Prospects of Thoria-Base Nuclear Fuels," pp. 289-310 in *Proc. Brit. Ceram. Soc.* 7 and ORNL-TM-1297 (November 1965).
37. F. W. Albaugh et al., *Reactor Fuels and Materials Development Program for Fuels and Materials Branch of USAEC Division of Reactor Development and Technology, Quarterly Progress Report, April-June 1967*, BNWL-473 (September 1967), p. 4.1.

APPENDIX A. CALIBRATION OF MOTION TRANSDUCERS

APPENDIX A. CALIBRATION OF MOTION TRANSDUCERS

Before installation each of the transducers was calibrated over the anticipated range of in-reactor operating conditions. During startup it became apparent that the transducers were being operated at temperatures higher than anticipated, and that a substantial thermal gradient existed along the axis of each transducer. To correct for this, we determined the effects of these conditions using an identical transducer in an out-of-reactor test apparatus. The results of these tests were then applied to the in-reactor transducers to correct for measured operating conditions. The coil temperatures were measured by the resistance technique described in Appendix H, and the thermal gradient along the transducers was measured by thermocouples attached to the transducer bodies.

Heat flow conditions existing in the test capsule were simulated in the tests by passing current through the mockup cladding to internally heat the transducers. External heaters were also used to obtain the desired axial gradients. Tests were made to prove that the direct-current heating of the cladding did not interfere with the transducer electronic signals. The output values with and without current flowing did not differ significantly.

Table A-1 lists the data gathered and various thermal conditions studied in the out-of-reactor tests. The data from run 13 were not used because it represented a thermal gradient opposite to that encountered in the reactor. Only the data for transducer core positions in the lower half of the transducer coils were used since all reactor operation data would be in this region.

The data, with the exclusions noted, were correlated by multiple regression analysis to obtain the following equation:

$$X = 32.07 V + 0.1227 V^2 + 0.0203 V(TL) - 0.5324 \Delta T + 302.5 ,$$

where

V = output voltage (dc) from signal conditioner,

TL = temperature ($^{\circ}\text{C}$) of the lower coil,

$\Delta T = TU - TL$,

T^U = temperature ($^{\circ}\text{C}$) of the upper coil, and

X = transducer core location (mils from starting position used in calibration setup).

The fit to the calibration data was quite good, giving a correlation coefficient of 0.999934 and a standard error of 1.153 mils. The constant in the last term of the above equation was adjusted for the reactor transducers to set $X = 0$ for the temperature, voltage, and displacement conditions existing at zero power on November 22, 1971. The values of the constants for the upper and lower transducers were 254.4 and 262.1, respectively.

Table A-1. Calibration Data for Motion Transducer

Run	Lower Coil Temperature ($^{\circ}\text{C}$)	ΔT^a ($^{\circ}\text{C}$)	Transducer Core Position ^b (in.)	Output Signal (V)
1	27	0	0	-9.521
1	27	0	0.05	-7.962
1	27	0	0.1	-6.378
1	27	0	0.15	-4.766
1	27	0	0.2	-3.16
1	27	0	0.25	-1.609
1	27	0	0.3	-0.067
1	27	0	0.35	1.473
1	27	0	0.4	3.028
1	27	0	0.45	4.595
1	27	0	0.5	6.168
1	27	0	0.55	7.749
1	27	0	0.6	9.273
2	73	-1	0	-9.313
2	73	-1	0.05	-7.772
2	73	-1	0.1	-6.202
2	73	-1	0.15	-4.637
2	73	-1	0.2	-3.091
2	73	-1	0.25	-1.58
2	73	-1	0.3	-0.086
2	73	-1	0.35	1.399
2	73	-1	0.4	2.896
2	73	-1	0.45	4.416
2	73	-1	0.5	5.955
2	73	-1	0.55	7.506
2	73	-1	0.6	9.015

Table A-1 (continued)

Run	Lower Coil Temperature (°C)	ΔT^a (°C)	Transducer Core Position ^b (in.)	Output Signal (V)
3	112	-5	0	-9.181
3	112	-5	0.05	-7.659
3	112	-5	0.1	-6.124
3	112	-5	0.15	-4.591
3	112	-5	0.2	-3.083
3	112	-5	0.25	-1.608
3	112	-5	0.3	-0.162
3	112	-5	0.35	1.287
3	112	-5	0.4	2.735
3	112	-5	0.45	4.209
3	112	-5	0.5	5.725
3	112	-5	0.55	7.24
3	112	-5	0.6	8.733
4	144	-5	0	-9.03
4	144	-5	0.05	-7.529
4	144	-5	0.1	-6.009
4	144	-5	0.15	-4.487
4	144	-5	0.2	-3.022
4	144	-5	0.25	-1.585
4	144	-5	0.3	-0.177
4	144	-5	0.35	1.226
4	144	-5	0.4	2.641
4	144	-5	0.45	4.101
4	144	-5	0.5	5.567
4	144	-5	0.55	7.071
4	144	-5	0.6	8.538
5	174	-10	0	-8.922
5	174	-10	0.05	-7.448
5	174	-10	0.1	-5.957
5	174	-10	0.15	-4.471
5	174	-10	0.2	-3.024
5	174	-10	0.25	-1.612
5	174	-10	0.3	-0.235
5	174	-10	0.35	1.145
5	174	-10	0.4	2.518
5	174	-10	0.45	3.938
5	174	-10	0.5	5.388
5	174	-10	0.55	6.878
5	174	-10	0.6	8.354

Table A-1 (continued)

Run	Lower Coil Temperature (°C)	ΔT^a (°C)	Transducer Core Position ^b (in.)	Output Signal (V)
6	27	0	0	-9.526
6	27	0	0.05	-7.971
6	27	0	0.1	-6.373
6	27	0	0.15	-4.774
6	27	0	0.2	-3.191
6	27	0	0.25	-1.624
6	27	0	0.3	-0.08
6	27	0	0.35	1.475
6	27	0	0.4	3.014
6	27	0	0.45	4.578
6	27	0	0.5	6.16
6	27	0	0.55	7.73
6	27	0	0.6	9.259
7	203	-7	0	-8.717
7	203	-7	0.05	-7.263
7	203	-7	0.1	-5.768
7	203	-7	0.15	-4.319
7	203	-7	0.2	-2.896
7	203	-7	0.25	-1.523
7	203	-7	0.3	-0.175
7	203	-7	0.35	1.161
7	203	-7	0.4	2.499
7	203	-7	0.45	3.885
7	203	-7	0.5	5.311
7	203	-7	0.55	6.774
7	203	-7	0.6	8.225
8	147	-26	0	-9.345
8	147	-26	0.05	-7.85
8	147	-26	0.1	-6.331
8	147	-26	0.15	-4.837
8	147	-26	0.2	-3.363
8	147	-26	0.25	-1.913
8	147	-26	0.3	-0.488
8	147	-26	0.35	0.942
8	147	-26	0.4	2.353
8	147	-26	0.45	3.823
8	147	-26	0.5	5.318
8	147	-26	0.55	6.848
8	147	-26	0.6	8.334

Table A-1 (continued)

Run	Lower Coil Temperature (°C)	ΔT^a (°C)	Transducer Core Position ^b (in.)	Output Signal (V)
9	201	-42	0	-9.319
9	201	-42	0.05	-7.843
9	201	-42	0.1	-6.371
9	201	-42	0.15	-4.904
9	201	-42	0.2	-3.473
9	201	-42	0.25	-2.076
9	201	-42	0.3	-0.71
9	201	-42	0.35	0.667
9	201	-42	0.4	2.048
9	201	-42	0.45	3.466
9	201	-42	0.5	4.929
9	201	-42	0.55	6.427
9	201	-42	0.6	7.91
10	235	-34	0	-8.969
10	235	-34	0.05	-7.535
10	235	-34	0.1	-6.077
10	235	-34	0.15	-4.632
10	235	-34	0.2	-3.242
10	235	-34	0.25	-1.88
10	235	-34	0.3	-0.546
10	235	-34	0.35	0.774
10	235	-34	0.4	2.116
10	235	-34	0.45	3.487
10	235	-34	0.5	4.901
10	235	-34	0.55	6.368
10	235	-34	0.6	7.828
11	27	0	0	-9.565
11	27	0	0.05	-8.004
11	27	0	0.1	-6.486
11	27	0	0.15	-4.798
11	27	0	0.2	-3.205
11	27	0	0.25	-1.631
11	27	0	0.3	-0.08
11	27	0	0.35	1.468
11	27	0	0.4	3.017
11	27	0	0.45	4.58
11	27	0	0.5	6.173
11	27	0	0.55	7.754
11	27	0	0.6	9.287

Table A-1 (continued)

Run	Lower Coil Temperature (°C)	ΔT^a (°C)	Transducer Core Position ^b (in.)	Output Signal (V)
12	80	-9	0	-9.465
12	80	-9	0.05	-7.928
12	80	-9	0.1	-6.369
12	80	-9	0.15	-4.801
12	80	-9	0.2	-3.257
12	80	-9	0.25	-1.743
12	80	-9	0.3	-0.255
12	80	-9	0.35	1.233
12	80	-9	0.4	2.745
12	80	-9	0.45	4.263
12	80	-9	0.5	5.818
12	80	-9	0.55	7.371
12	80	-9	0.6	8.89
13	118	41	0	-8.4
13	118	41	0.05	-6.858
13	118	41	0.1	-5.324
13	118	41	0.15	-3.81
13	118	41	0.2	-2.33
13	118	41	0.25	-0.898
13	118	41	0.3	0.507
13	118	41	0.35	1.899
13	118	41	0.4	3.3
13	118	41	0.45	4.719
13	118	41	0.5	6.174
13	118	41	0.55	7.636
13	118	41	0.6	9.079
14	27	0	0	-9.538
14	27	0	0.05	-7.983
14	27	0	0.1	-6.376
14	27	0	0.15	-4.785
14	27	0	0.2	-3.191
14	27	0	0.25	-1.624
14	27	0	0.3	-0.076
14	27	0	0.35	1.465
14	27	0	0.4	3.007
14	27	0	0.45	4.572
14	27	0	0.5	6.154
14	27	0	0.55	7.728
14	27	0	0.6	9.201

^aUpper coil temperature minus lower coil temperature.^bMeasured from a fixed starting position.

APPENDIX B. LIST OF ENGINEERING DRAWINGS

APPENDIX B. LIST OF ENGINEERING DRAWINGS

The following is a list of the pertinent engineering drawings. They are all designated by suffixes of the ORNL Reactor Division drawing number M-10571-RM, entitled "MINT-1 Fuel Cladding Mechanical Interaction Capsule."

Suffix	Description
-001 E, Rev. 7	Parts list
-002 E, Rev. 6	Assembly lower section
-003 E, Rev. 3	Assembly upper section
-004 E, Rev. 4	Fuel element subassembly and details
-005 E, Rev. 6	Weldments and details
-006 E, Rev. 3	Details
-009 E, Rev. 4	Lead tube details
-010 D, Rev. 2	Elbow weldment and details
-011 E, Rev. 4	Details
-013 D, Rev. 5	Weldment and details
-015 D, Rev. 6	Information assembly
-016 D, Rev. 1	Bellows weldments and details

APPENDIX C. HEATING3 THERMAL ANALYSIS

APPENDIX C. HEATING3 THERMAL ANALYSIS

The following describes the heat transfer analysis performed and the results obtained using the HEATING3 code¹ to determine effects of thermocouples, eccentric fuel element, and uneven power on the temperatures of capsule components.

The test design for which the heat transfer calculations were made had the following basic parameters:

1. fuel diameter, 0.20 in.;
2. cladding thickness, 0.015 in.;
3. thermocouples, 1/16 in. diam, brazed to the inside of the primary containment;
4. primary containment, stainless steel, 0.420 in. ID, 0.040 in. thick;
5. helium gap (between primary and secondary containment) was a contact fit, 0.0005 in. assumed; and
6. secondary containment, stainless steel, 0.50 in. ID, 0.060 in. thick.

The space between the fuel cladding and the primary containment, which also includes the thermocouples, is filled with NaK. The thermocouples are arranged three on each side initially, separated as shown in Fig. C-1(a); then two (center couple removed), and finally one.

We recognize that the reduction from two thermocouples to one shifts the axis of symmetry; however, calculations for off-center fuel effects and off-center power effects were made for the worst case (i.e., conservative calculations).

Three different cases were studied at three different linear power rates. Case 1 specified even power distribution with the fuel element centered inside the primary containment. The results for this case are summarized in Tables C-1, C-2, and C-3.

Case 2 specified one thermocouple on each side and the fuel element displaced until it contacted the thermocouple on one side. The results for this case are summarized in Table C-4, and the case is pictured in Fig. C-1(b).

Case 3 specified one thermocouple on each side and the fuel centered, but the power varying +10% on one side and -10% on the other side. The results of this case are summarized in Table C-5.

BLANK PAGE

(a) Fuel Element Centered

(b) Fuel Element Eccentric

Fig. C-1. MINT-1 Geometries Used for HEATING3 Heat Transfer Analysis.

Table C-1. Capsule Temperatures for Case 1 — One Thermocouple (TC), Fuel Centered, Even Power

Power (kW/ft)	Angular Location Relative to TC	Temperature, °C, for Various Radial Locations				
		Cladding Outer Surface	TC	Inside Surface SS1	Outside Surface SS1	Inside Surface SS2
19	at TC	678	493	383	319	234
	90°	653		431	344	246
16	at TC	599	440	345	291	217
	90°	578		387	312	228
10	at TC	431	327	265	229	181
	90°	416		294	243	188

Table C-2. Capsule Temperatures for Case 1 - Two Thermocouples, Fuel Centered, Even Power

Power (kW/ft)	Angular Location Relative to TC's	Temperature, °C, for Various Radial Locations				
		Cladding Outer Surface	TC	Inside Surface SS1	Outside Surface SS1	Inside Surface SS2
19	at TC	690	502	390	324	237
	between	681		436	346	247
	90°	667		439	350	250
16	at TC	610	448	352	294	219
	between	602		392	313	228
	90°	590		394	317	230
10	at TC	438	333	270	232	183
	between	433		297	244	188
	90°	425		299	247	190

Table C-3. Capsule Temperatures for Case 1 - Three Thermocouples, Fuel Centered, Even Power

Power (kW/ft)	Angular Location Relative to Middle TC	Temperature, °C, for Various Radial Locations				
		Cladding Outer Surface	TC	Inside Surface SS1	Outside Surface SS1	Inside Surface SS2
19	Middle TC	725	516	388	322	234
	Outer TC	715	514	393	326	237
	90°	679		447	356	253
16	Middle TC	640	460	351	292	217
	Outer TC	632	459	354	296	220
	90°	601		402	322	233
10	Middle TC	458	340	268	230	181
	Outer TC	452	340	271	232	183
	90°	432		303	250	192

Table C-4. Capsule Temperatures for Case 2 -- Eccentric Fuel Element,
One TC in Contact with Cladding, Even Power

Power (kW/ft)	Angular Location Relative to TC Contact	Temperature, °C, for Various Radial Locations				
		Cladding Outer Surface	TC	Inside Surface SS1	Outside Surface SS1	Inside Surface SS2
19	0°	737	544	437	360	258
	180°	682	472	362	303	224
	90°	667		441	352	251
16	0°	649	526	391	325	237
	180°	606	421	327	276	208
	90°	588		395	318	231
10	0°	466	384	296	252	194
	180°	436	315	253	219	175
	90°	424		299	247	191

Table C-5. Capsule Temperatures of Case 3 -- Fuel Element Centered,
One TC, Power Varying Linearly 20% Across Fuel Through
The TC's

Power (kW/ft)	Angular Location Relative to High Power Side	Temperature, °C, for Various Radial Locations				
		Cladding Outer Surface	TC	Inside Surface SS1	Outside Surface SS1	Inside Surface SS2
19	0°	753	521	392	326	238
	180°	716	501	380	316	232
	90°	712		431	344	247
16	0°	662	462	352	295	219
	180°	631	446	342	287	215
	90°	627		387	311	227
10	0°	472	341	270	232	183
	180°	453	331	263	227	180
	90°	451		293	243	188

A careful check of the output from the HEATING3 code for these cases showed correct calculation for test case data where comparison was made with calculations by the GENGTC code² and consistency in actual case output, so we believe confidence can be placed in these results.

To establish the basic equation given in Sect. 6 relating the average cladding temperature at any elevation to the thermocouple readings the values for T_E and T were obtained from Case 1 with two thermocouples as described in Table C-2. The T value was calculated as follows:

$$T = \frac{2T_C + T_A + T_B}{4},$$

where

T_A = temperature of cladding at a thermocouple location,

T_B = temperature of cladding between the two thermocouples,

T_C = temperature of cladding at a location 90° from the thermocouples,
and

T = average surface temperature around the cladding at the two-thermocouple location.

REFERENCES FOR APPENDIX C

1. W. D. Turner and M. Siman-Tov, *HEATING3: An IBM 360 Heat Conduction Program*, ORNL-TM-3208 (February 1971).
2. H. C. Roland, *GENGTC, A One-Dimensional GEIR Computer Program for Capsule Temperature Calculations in Cylindrical Geometry*, ORNL-TM-1942 (December 1967).

APPENDIX D. FUEL DATA.

APPENDIX D. FUEL DATA

The following tables give the chemical, physical, and dimensional characterization of the fuel used in the MINT-1 experimental fuel pin. Figure D-1 shows design dimensions of the fuel pellets.

SUMMARY OF ORNL ANALYTICAL DATA ON (U,Pu)O₂ PELLETS
AS RECEIVED FROM BNWL

Isotopic Analysis

²³³ U	<0.0002	²³⁹ Pu	86.24
²³⁴ U	0.0054	²⁴⁰ Pu	11.92
²³⁵ U	0.727	²⁴¹ Pu	1.68
²³⁶ U	0.0006	²⁴² Pu	0.160
²³⁸ U	99.27	²⁴⁴ Pu	<0.0003

Heavy Metal Analysis

% U	66.25
% Pu	21.98
Pu/(U + Pu)	24.9%

Surface Area

<0.7 m²/g

Density by Hg Pycnometry

Bulk 9.66 g/cm³

At 10,000 psi Hg pressure 10.66 g/cm³

Fig. D-1. MINT-1 Fuel Pellet

Spectroscopic Impurity Determinations

Element	Impurity Levels, ppm	
	Emission Spectroscopy	Spark Source Mass Spectroscopy
Al	<38	150
B		2
Ba		3
Ca		20
Cd	<377	
Co		0.1
Cr	<38	3
Cu	SNF*	6
Fe	<94	30
K		0.8
Mg		15
Mn	<19	0.3
Mo	<38	<0.2
Na		0.5
Nb	SNF	
Ni	<38	20
P		2
Pb	SNF	80
Si	<94	30
Sn	SNF	
Ta		10
Ti	<9.4	30
V	SNF	0.1
W		<0.4
Zn	SNF	
Zr	<19	10
Rare Earth		4
S		1500

*Sought, not found.

Miscellaneous Chemical Analyses

	<u>Reported Values</u>	<u>Average</u>
Oxygen-to-metal ratio	1.971, 1.982	1.976
Gas Content	0.14, 0.15, 0.16	0.15
Moisture Content	Not determined	
C	<20 ppm	
N	150 ppm	
F	8 ppm	
Cl	13 ppm	

Summary of Oxygen-to-Metal Ratio, Gas Release, and Water Analyses
on (U,Pu)O₂ Pellets after Final Heat Treatment at ORNL

	Oxygen- to-Metal Ratio	Gas Release (cm ³ /g)	H ₂ O, ppm		
			Ambient ^a	On Heating to 1000°C ^b	Total
Three Determinations	1.951	0.04	4	18	22
	1.954	0.02	16	21	37
	1.953	0.03	25	21	46
Average	1.953	0.03	15	20	35
95% Confidence Interval	0.004	0.01	26	4.2	30

^aH₂O measured while flowing dry nitrogen over pellet at ambient.
Large variation believed to be due to introduction of air into system
while loading pellet.

^bH₂O measured on heating from ambient to 1000°C.

Dimensions, Densities, and Positions of Pellets in MINT-1 Fuel Pin

Pellet Position	Length (in.)	Weight (g)	Density (%) of Theoretical)
1	0.22685	1.044	88.6010
2	0.22315	1.031	88.7032
3	0.22275	1.0315	88.6291
4	0.2269	1.0715	90.1520
5	0.22575	1.0575	89.3444
6	0.2197	1.036	89.9034
7	0.22185	1.027	88.6092
8	0.22025	1.0335	89.4570
9	0.2334	1.105	90.1318
10	0.22005	1.0205	88.5069
11	0.22735	1.055	88.5839
12	0.23065	1.083	89.6973
13	0.2218	1.043	89.8214
14	0.2196	1.0375	90.0756
15	0.2196	1.038	90.0245
16	0.22425	1.050	89.8839
17	0.22235	1.0435	89.9200
18	0.2203	1.0245	88.7505
19	0.2201	1.0245	88.8332
20	0.2184	1.031	90.2047
21	0.22485	1.062	89.9979
22	0.2192	1.0265	89.4751
23	0.21645	0.9975	88.5446
24	0.2234	1.0375	88.8789
25	0.2176	1.025	90.0177
26	0.22295	1.0375	88.9691
27	0.2200	1.0195	88.9072
28	0.2209	1.029	88.7990
29	0.22615	1.0605	90.0016
30	0.2312	1.080	89.1374
31	0.22045	1.032	89.4318
32	0.2120	0.9965	90.0753
33	0.2226	1.0375	89.2062
34	0.2207	1.0225	88.6920
35	0.22235	1.0425	89.7394
36	0.22095	1.0295	88.8215
37	0.22345	1.0465	89.8182
38	0.2223	1.0395	89.1263
39	0.2260	1.0665	89.8140
40	0.22605	1.0635	89.6351
41	0.2265	1.063	89.1299
42	0.23745	1.115	89.5434
43	0.2184	1.010	88.5534

Fuel Column Properties

Stack height, in.	9.59
Stack weight, g	44.83
Cladding ID, in.	0.1995
Smear density, % of theoretical	
Fuel column	83.29
Planar	85.32
Average diameter, in.	0.1949
Standard deviation	0.000268
Average pellet density, % of theoretical	
Standard deviation	89.35
	0.566

APPENDIX E. BULKHEAD BRAZE SPECIFICATION MET-FCT-PP-42

(Procedure developed for and used with the MINT-1 capsule)

Fuel Cycle Technology
Metals and Ceramics Division
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee

Procedure No. MET-FCT-PP-42

Date September 29, 1971

Page 1 of 4

PROCESS PROCEDURE

Title: Procedure for Vacuum Brazing Stainless Steel Bulkhead Assemblies for Capsule Irradiation Experiments

Prepared by: R. B. Fitts, B. Fleischer, D. E. Fitts, R. B. Fitts

Approved by: G. M. Slaughter, T. N. Washburn

QA Approval: W. J. Werner

1. Scope

This document sets forth the procedure for brazing stainless steel bulkhead assemblies with Nicrobraz 50 brazing alloy and provides a standard data sheet for collection of required information.

2. General Information

The time and cost involved in processing high quality materials and parts for irradiation test equipment require that extreme care be exercised in handling and assembly operations. Without exception, data sheet D-202 must be completed while processing each brazement and each section completed before initiating the next operation.

3. Materials

Stainless steel bulkheads, tubes, and sheathed thermocouples fabricated from AISI types 304, 304H, 304L, 316, 316H, 316L, 321, and 347.

4. Assembly

- 4.1 All cleaning and assembly operations shall be done in the presence of a technical representative (technician or engineer) from the Ceramics Fuels Irradiation (CFI) group.
- 4.2 The mating surfaces of all parts to be brazed shall be lightly sanded with 320 to 600 grit paper to assure removal of any oxide film. Use only clean papers and do not alter part dimensions beyond drawing limits. The diametrical clearance between parts should be 0.002 to 0.004 in.
- 4.3 Clean all parts ultrasonically in acetone and ultrasonically rinse in 200 proof ethanol. Dry with forced hot air gun.

Procedure No. MET-FCT-PP-42

Date September 29, 1971

Page 2 of 4

- 4.4 After cleaning, the parts should be handled only with the aid of clean surgical gloves during all assembly operations.
- 4.5 Assembly should be done in accordance with drawings furnished by the CFI group.

5. Application of Braze Alloy

A batch of brazing slurry shall be prepared by mixing Microbraz 50 alloy with Microbraz Cement in a clean, new container. The mixture shall be prepared using 10 drops of cement for each 1.6 g of brazing alloy.

- 5.1 Prior to applying the braze slurry to the assembly, verify that the joint is properly assembled per drawing, sketch, or other information.
- 5.2 The brazing slurry shall be spread over the top of the bulkhead around the joint areas. A minimum amount of the slurry shall be used in order to minimize the spread of braze metal beyond the joint region. Microbraz Green Stop-Off shall be applied to each side of the bulkhead around each braze joint to prevent braze alloy from running to areas that will subsequently be welded. This shall also be applied to the ends of the tubes that terminate near the bottom of the bulkhead to prevent plugging of the tubes. The stop-off must also be applied to the thermocouple on both sides of the joint to minimize braze metal embrittlement. The stop-off should be applied only after the braze slurry is dry. It should be placed at least an 1/8 in. away from the dry slurry. To accurately apply the braze slurry and stop-off materials in these intricate areas, use a sharpened wood dowel (Q-tip stem works well).
- 5.3 The approximate amount of brazing slurry applied to the joint shall be recorded on D-202.
- 5.4 The brazing slurry and stop-off shall be allowed to air dry for 30 min. prior to placing into the furnace.

6. Installation in the Furnace

The work-piece is to be located in the furnace with the braze joint area centered in the hot zone. Check to verify that assembly is properly assembled. A control thermocouple is to be located within 1/2 in. of the braze joint and used for control and recording of the brazing temperature cycle. The thermocouple should touch the parts to be brazed.

7. Heating Cycle

The furnace is to be sealed and evacuated to a vacuum of 5×10^{-5} torr or better for at least 30 min prior to heating. A maximum heating rate of $50^{\circ}\text{C}/\text{min}$ is to be employed until the joint temperature reaches 1030°C . The temperature is to be held at 1030°C for 5 min and then cooled at a rate of $30^{\circ}\text{C}/\text{min}$ to 600°C . At this temperature the furnace is to be turned off and the temperature allowed to reach room temperature before the vacuum is broken and the assembly removed.

8. Cleaning

8.1 Stop-off may be removed mechanically or by pickling lightly in a 150°F water solution of 10% nitric acid and 2% hydrofluoric acid.

8.2 The braze joint shall be thoroughly cleaned by washing in acetone followed by an alcohol rinse and drying with a heat gun.

9. The procedure is to be qualified for each joint configuration by preparing two consecutive braze joints, each of which receives and passes inspection as described in Sect. 10 of this procedure. These qualification brazes shall be made with parts from the same lots of materials as the actual capsule components.

10. Inspection

Subsections 10.1 and 10.2 are to be applied to both final brazes and qualification brazes. All subsections in this section are applied to qualification brazes.

10.1 Visual inspection - The entire bulkhead shall be inspected with a $3\times$ stereomicroscope. A complete fillet shall exist around each part penetrating the bulkhead. No braze metal is permitted on areas of the bulkhead requiring subsequent joining to other parts of the capsule assembly. The tubes shall not be plugged with braze metal.

10.2 Helium leak check - Each brazed assembly shall be helium leak checked per PP-23 substituting the word "brazes or brazed" for the words "welds or welded."

10.3 Metallographic examination - This subsection applies to qualification brazes only.

10.3.1 Sectioning for metallography - Each brazed assembly shall be cut in half along an axial plane which shall reveal as much of the brazed joints as possible. One-half shall be mounted for polishing of the cut surface. The other half shall be further cut in half, perpendicular to the original cut, near the midplane of the braze joint. These two pieces shall be mounted for polishing of the second cut surface.

Procedure No. MET-FCT-PP-42

Date September 29, 1971

Page 4 of 4

10.3.2 The polished surfaces shall be examined at 50 $\times$, 200 $\times$, and 500 $\times$ and approved by the project engineer and a metallurgist from the Welding and Brazing Laboratory. Representative record photographs shall be provided as necessary. Special attention shall be given to the following items.

10.3.2.1 Surface cracks in braze fillet - these should not be deeper than 0.001 in.

10.3.2.2 Interaction of the base metal with the braze filler material or stopoff material shall not penetrate deeper than 10% of the base metal thickness or 0.002 in., whichever is least.

10.3.2.3 Porosity, inclusions, or internal cracks - defects of this type shall not cover more than 10% of the braze metal surface visible on any metallographic section.

10.3.2.4 Cracks along base metal/braze metal interface - this type of defect shall cause rejection of the joint.

References

MET-FCT-D-202 Brazing Data Sheet
MET-FCT-PP-23 Helium Leak Testing of Capsules

BRAZING RECORD

A. Project Title _____

B. Component Information

<u>Part Name or Description</u>	<u>Drawing Number</u>	<u>Part Number</u>	<u>Unit Number</u>	<u>Inspection Report No.</u>
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____
_____	_____	_____	_____	_____

C. Cleaning of Components

Performed by _____ Date _____

D. Assembly

Name of assembly _____

Dwg. No. _____ Unit Ident. No. _____

Assembled by _____

Assembly checked by (CFI Rep.) _____

E. Braze Filler Preparation and Application

Amount of filler metal in batch _____

Amount of cement in batch _____

Estimate of quantity of slurry used
(wt, drops, etc.) _____

Applied by _____ Date _____

F. Stop-off Application

Applied by _____

Checked by (CFI Rep.) _____ Date _____

G. Furnace Cycle

Furnace location _____ Manufacturer _____

Vacuum history: Before heatup _____ torr

Maximum during heating _____ torr

Before cooldown _____ torr

Before opening furnace _____ torr

Temp history: Heatup time _____ min

Brazing temp _____ °C

Holding time _____ min

NOTE: Attach copy of strip chart record of temperature.

Furnace operator _____ Date brazed _____

H. Inspections

Visual: Accepted by _____ Rejected by _____

Cause for rejection _____

He leak check: Accepted by _____ Rejected by _____

Estimated leak rate _____

Metallograph results (qualifying units only):

Metallograph numbers _____

Print numbers _____

Accepted by _____ Rejected by _____

Cause for rejection _____

**APPENDIX F. PRIMARY CONTAINER-THERMOCOUPLE BRAZE ASSEMBLY
SPECIFICATION MET-FCT-PP-38**

The following procedure is that developed for and used to attach the thermocouples to the inside of the primary containment wall in the MINT-1 capsule.

Fuel Cycle Technology
Metals and Ceramics Division
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee

Procedure No. MET-FCT-PP-38
Date November 16, 1971
Page 1 of 7

PROCESS PROCEDURE

Title: Procedure for Brazing Thermocouples to Primary Container for
Mechanical Interaction Assembly

Prepared by: B. Fleischer, J. W. Hendricks, R. L. Senn

Approved by: T. N. Washburn

QA Approval: W. J. Werner 3/9/72

1. Scope

This procedure covers all operations for production of the subject assembly brazement starting with the uncleaned, finished machined parts, and ending with the completely inspected subassembly.

2. General

2.1 All drawing numbers cited herein are suffixes of OKNL
Dwg. No. M-10571-RM.

2.2 Description of Subassembly -

This brazement consists of six thermocouples brazed to the inside wall of the primary containment tube, as shown in Dwg. 005-E, Rev. 6. The thermocouples are inserted into the subassembly through the six holes in the primary containment end cap in accordance with the following: two are placed 1.2 in. from the end cap reference (see dwg); two are placed 5.2 in. from the reference; and two are placed 9.3 in. from the reference. Each pair described above is to be placed against the inside wall of the tube diametrically opposed and in line with the other two pairs (see dwg). Placement of these thermocouples is intricate, requiring a spacing mandrel to internally position and hold the thermocouples throughout the brazing cycle. Placement of the brazing alloy on the thermocouples for the interior joints is accomplished by plating prior to final positioning of the thermocouples.

2.3 A route card enumerating all operations to be performed will accompany the subassembly at all times. After completion of an operation, the person responsible for that operation shall sign the route card.

3. Preassembly Cleaning of Parts

3.1 Thermocouples (TE's)

The following operations apply to a 6-ft length of the TE's measured from the sensing end.

BLANK PAGE

Procedure No. MET-FCT-PP-38Date November 16, 1971Page 2 of 7

3.1.1 Remove all tapes and labels and adhesive residues from these products. Carefully inspect these areas to make certain that all residues have been removed.

3.1.2 Straighten the TE's.

3.1.3 Wipe with clean acetone-soaked cloths to remove all traces of grease and/or dirt.

3.1.4 Remove acetone residue by wiping with clean cloths soaked with ethyl alcohol (ethanol).

3.1.5 Repeat steps 3.1.3 and 3.1.4 until white lint-free ethanol-soaked cloth shows no residue when sheath is wiped.

3.2 Primary Weldment-

Finish machined subassembly composed of parts 1-2-1, 1-2-3, and 1-2-4 as shown on Dwg. 005-E, Rev. 6.

3.2.1 Immerse primary weldment in tank of ultrasonic cleaner filled with Dow Clene WR (1-1-1 trichlorethane). Energize ultrasonic cleaner until no residues are observed coming from parts (minimum of 20 min).

3.2.2 Allow parts to air dry.

4. Assembly

4.1 Check that thermocouples are properly labeled and assign TE numbers.

4.2 Assemble TE's in the primary container in their proper radial positions as shown on Dwg. 005-E, Rev. 6.

4.3 Affix ~18 in. length of TE's to a temporary mandrel inside the container to maintain their alignment. The TE's should extend about 20 in. beyond the container to provide adequate length for plating operations.

4.4 Cover assembly with polyethylene sheet such that all parts are covered during transport to and from plating shops.

5. Plating of Braze Alloy on Thermocouples

5.1 General -

The following precautions should be noted during handling and processing in both plating operations.

-
- 5.1.1 Avoid bending, scratching, or abrasion of thermocouples particularly over the length starting 2 in. above the primary weldment bulkhead and extending down to the ends to be plated.
 - 5.1.2 Protect the thermocouples and primary weldment from dirt, greases, vapors, etc. over the length described in Sect. 5.1.1.
 - 5.1.3 Any tapes or masking materials used on the above surfaces shall be completely removed without damage to or contamination of the surfaces.
 - 5.1.4 Do not move the primary container with respect to the thermocouples.
 - 5.2 Nickel Plating -
Using the Kanigen electroless nickel plating process (or equivalent) as outlined in the K-25 Kanigen Plating Manual, plate 0.001 ± 0.0005 in. of nickel on the areas specified in Fig. 1.
 - 5.3 Chromium Plating -
Using conventional chromium electroplating procedures, plate 0.0002 in. of hard chromium on nickel-plated areas as shown in Fig. 1.
 - 5.4 A 12-in.-long control sample shall also be made concurrently with the above to assure that the correct composition has been obtained.
6. Postplating Cleaning Operations
- 6.1 Remove all tapes and labels and all adhesive residues of these materials on the portion of the TE's below the primary container.
 - 6.2 Degrease these areas by wiping with clean acetone-soaked cloth.
 - 6.3 Remove all discolorations between the plated areas and the primary container by lightly polishing with fine emery paper followed by acetone rinsing. Remove acetone residue with ethanol.
 - 6.4 After inspecting to assure removal of all foreign materials, carefully slide primary container down until the TE's extend only about 10 in. beyond the end of the container.
 - 6.5 Place primary container and plated tips into beaker filled with trisodiumphosphate solution (50 cm^3 trisodiumphosphate per liter of de-ionized or distilled water). Solution must cover assembly at least 3 in. above point where thermocouples exit from top of containment.
 - 6.6 Place beaker in ultrasonic cleaning tank and energize until no residue comes from parts (minimum of 20 min.).
 - 6.7 Allow parts to air dry. Handle with gloves from this point.

-
- 6.8 Place subassembly in beaker filled with fresh Dow Clene WR and ultrasonically clean for a minimum of 20 min.
 - 6.9 Allow parts to air dry.
 - 6.10 Inspect visually and by wiping with lint-free ethanol-soaked cloth to ensure that parts are free of contaminants. Repeat above steps if evidence of contaminants remain.
 - 6.11 Attach thermocouple jacks to all thermocouples.
 - 6.12 Seal parts in polyethylene for transfer to brazing laboratory.
 7. Preparation and Fixturing for Brazing
 - 7.1 Fabricate a mandrel in accordance with the drawing shown in Fig. 2 for fixturing the thermocouples in the primary container. The spacer surfaces which will contact the thermocouples and end "A" shall be coated with Microbraz Green Stop-Off or its equivalent to prevent flow and adhesion of the braze alloy to the mandrel. Clean mandrel with acetone and ethanol prior to use.
 - 7.2 Place the thermocouples on the mandrel so their hot junctions are in the correct positions relative to end "A" of the mandrel. End "A" indexes to the inside of the end cap when the mandrel is fully inserted into the container. Refer to Dwg. 005-E, Rev. 6 for proper location of the thermocouples with respect to the end cap. Note that these dimensions are indexed to the outside of the end cap and therefore are 1/8 in. longer than required since the mandrel indexes to the inside of the end cap. The thermocouples should be secured at various places along their length with shrinkable plastic tubing. Only unplated areas of the thermocouples contact the mandrel spacers.
 - 7.3 Slide the container down over the thermocouple bundle, removing the plastic tubing as the thermocouples go inside the container. Care must be exercised to assure that the thermocouples do not slip relative to the mandrel during insertion. When end "A" of the mandrel indexes to the inside of the end cap, the thermocouples should be in proper position. The mandrel remains inside the container to hold the thermocouples firmly against the container wall during brazing.
 - 7.4 Apply one drop of a thick slurry of Microbraz 50 and Microbraz Cement to the outside of each thermocouple at the end cap penetration joint.
 - 7.5 Place Microbraz Green Stop-Off on each thermocouple outside the end cap and on the container wall about 1/8 in. away from the braze alloy after the braze alloy has dried. This is to keep braze alloy from running onto these critical surfaces during brazing.

8. Brazing

- 8.1 Prior to brazing the assembly, one half of the control sample should be brazed to a test plate to check the suitability of the alloy, using the equipment and technique described in Sect. 8.2.
- 8.2 Use a dry helium muffle tube furnace with at least a 10-in.-long uniform hot zone held at 1060°C. Insert the assembly and hold at 1060°C for 10 min. The thermocouples being brazed are used to monitor the assembly temperature. The assembly is cooled in the furnace atmosphere by moving it into the cold zone of the muffle tube. After the assembly has cooled below 200°C it can be removed from the furnace. A strip chart record of the temperature history shall be obtained and filed. A copy shall be sent to the project engineer.

9. Postbrazing Inspection

- 9.1 Remove the mandrel from the inside of the container. The mandrel should remove easily since the spacers should be free of braze alloy and are thin and flexible.
- 9.2 Visually inspect the thermocouple penetration joints to determine if fillets are complete on each joint and if any cracks are present in the braze area at 10× magnification. Record results. Lack of complete fillets is cause for rejection.
- 9.3 Visually inspect interior of container using a borescope to determine if the thermocouples have brazed in the plated areas. Record results. Lack of brazing is cause for rejection.
- 9.4. Leak check the end cap penetration joints in accordance with the following.
 - 9.4.1 Measure and record leak detector (LD) response to background and standard leak ($<5 \times 10^{-10}$ atm cm²/sec) before test piece is valved into LD.
 - 9.4.2 Evacuate interior of primary containment through the helium LD. A temporary helium leak-tight seal must be affixed to the hole still remaining in the end cap. Heat shrinkable plastic tubing is acceptable.
 - 9.4.3 After LD sensitivity is established, valve in test piece, spray helium over exterior of test piece, and watch for LD response.
 - 9.4.4 A helium leak rate greater than 1×10^{-9} atm cm³/sec shall be cause for rejection.

10. Records

- 10.1 Results of all inspections shall be recorded with date of inspection, type of inspection, and signature of person performing inspection.
- 10.2 A copy of these records shall be sent to the project engineer.

ORNL-DWG 72-2216

Fig. 1. Thermocouple Plating Plan.

ORNL-DWG 72-2217

MATERIALS	
ITEM NO.	DESCRIPTION
1	ROD, 1/8-in. diam AISI Type 300 Series Stainless Steel
2	SHEET, 0.005-in. thk AISI Type 300 Series Stainless Steel

Fig. 2. Braze Manifold.

APPENDIX G. COMPUTATION METHOD FOR ESTIMATING THE AVERAGE SURFACE TEMPERATURE ALONG THE CLADDING

This method is a modification of Simpson's rule. A modification was required because the temperature sensors were not equally spaced along the cladding axis. A schematic of the thermocouple arrangement is shown in Fig. G-1. We assume that the temperature distribution along the fuel element can be adequately described by the quadratic equation

$$T = Ax^2 + Bx + C , \quad (G-1)$$

where x is distance below the midplane thermocouples (x is negative above the midplane). The average temperature is then determined by the equation

$$T_{av} = \frac{\int_a^b (Ax^2 + Bx + C) dx}{l} , \quad (G-2)$$

where

a = distance from midplane thermocouples to the top of the cladding (negative),

b = distance from midplane thermocouples to the bottom of the cladding, and

l = length of the cladding.

Solution of Eq. (G-1) at the three locations, midplane (M), top (T), and bottom (B), and integration of Eq. (G-2) yields the following:

$$\text{at } T_M: \quad x = 0 \text{ and } T_M = A(0)^2 + B(0) + C , \quad (G-3)$$

therefore, $T_M = C$;

$$\text{at } T_T: \quad x = -3.6 \text{ and } T_T = A(-3.6)^2 + B(-3.6) + C , \quad (G-4)$$

therefore, $T_T = 12.96A - 3.6B + C$;

$$\text{at } T_B: \quad x = 4.6 \text{ and } T_B = A(4.6)^2 + B(4.6) + C , \quad (G-5)$$

Fig. G-1. Thermocouple Location Along the Fuel Element Cladding.

therefore, $T_B = 21.16A + 4.6B + C$.

$$\text{For } T_{av} = \frac{\int_{-4.2}^{5.5} (Ax^2 + Bx + C) dx}{9.7},$$

$$T_{av} = 8.263A + 0.65B + C. \quad (G-6)$$

Solution of Eqs. (G-3), (G-4), and (G-5) yields

$$A = 0.0264T_B - 0.0603T_M + 0.0339T_T,$$

$$B = 0.0264T_B + 0.0603T_M - 0.1559T_T,$$

$$C = T_M,$$

and substitution of these values of A , B , and C in Eq. (G-6) provides the solution for the average temperature given below:

$$T_{av} = 0.179T_T + 0.541T_M + 0.280T_B .$$

For computing T_{av} , the values of T_T , T_M , and T_B are the average values calculated with the equation described in Sect. 6 for determining the average cladding surface temperature adjacent to each particular thermocouple. For example,

$$T_T = \frac{T_{105} + T_{106}}{2} ,$$

where

$$T_{105} = -8.95 + 1.21(TE_{105}) + 3.15 \times 10^{-4}(TE_{105})^2 - 7.87 \times 10^{-8}(TE_{105})^3 ,$$

$$T_{106} = -8.95 + 1.21(TE_{106}) + 3.15 \times 10^{-4}(TE_{106})^2 - 7.87 \times 10^{-8}(TE_{106})^3 ,$$

and TE_{105} and TE_{106} are the readings of the two thermocouples (105 and 106) located near the top of the fuel pin.

APPENDIX H. CORRELATIONS OF THERMOCOUPLE AND TRANSDUCER COIL TEMPERATURES

APPENDIX H. CORRELATIONS OF THERMOCOUPLE AND TRANSDUCER COIL TEMPERATURES

Internal heat generation from absorption gamma radiation inside the transducers caused the coil temperatures to be higher than those measured by thermocouples attached to the transducer casings. To correct for this condition, the coil temperatures were determined by measuring resistance changes at various power levels and calculating the temperatures from a correlation of relative resistance change as a function of temperature. The correlation between resistance change and temperature was established from resistance measurements made during heating of a spare transducer. The following relation was determined:

$$T_{\text{coil}} = [261R(T)/R(25)] - 236 ,$$

where

$R(T)$ = coil resistance (ohms) at any temperature $T(^{\circ}\text{C})$,

$R(25)$ = coil resistance (ohms) at 25°C , and

T_{coil} = coil temperature ($^{\circ}\text{C}$).

The resistance value for each coil at 25°C was determined by measuring the coil resistance under isothermal conditions when the reactor was shut down. The value of T_{coil} could then be calculated for any measured value of $R(T)$ under operating nonisothermal conditions.

The three-wire connection to the coils permitted elimination of the lead wire resistance in the coil resistance determination, assuming that the lead wires had equal resistance. Any slight inequality in lead wire resistance would add a small uncertainty that would remain constant even as the coil temperature changed. The compensation method is shown in the sketch in Fig. H-1.

The relationship between coil temperature and thermocouple temperature was established to take advantage of automatic thermocouple temperature recording by the high-speed data logger used with the MINT-1 experiment. This correlation was established by measuring the coil temperature as described above and simultaneously recording the associated thermocouple value. This was done at various power levels. The data were then

Fig. H-1. Compensation Method for Determining Coil Resistances Measured at the Instrument Panel.

least-squares fitted to a polynomial equation of the following form:

$$T_{\text{coil}} = A + BT + CT^2,$$

where

T = thermocouple temperature ($^{\circ}\text{C}$), and

T_{coil} = coil temperature ($^{\circ}\text{C}$) measured by resistance technique.

The value of the constants in the above equation for each transducer at the three different thermal conditions present during operation are presented in Table H-1.

Table H-1. Equations for Correlation Between Coil and Thermocouple Temperatures

Period of Operation	Transducer	Correlations ^a	
		Upper Coil	Lower Coil
No shield (11/22/71-2/29/72)	Upper	$T_{UU} = -17.1 + 1.47(TE_{113})$	$T_{UL} = -17.9 + 1.57(TE_{112})$
	Lower	$T_{LU} = -23.4 + 1.70(TE_{111})$	$T_{LL} = -60.7 + 2.65(TE_{110})$
Stainless steel shield (3/1/72-5/9/72)	Upper	$T_{UU} = 6.32 + 0.918(TE_{113})$ $+ 3.23 \times 10^{-3}(TE_{113})^2$	$T_{UL} = -9.13 + 1.35(TE_{112})$ $+ 1.14 \times 10^{-2}(TE_{112})^2$
	Lower	$T_{LU} = 2.16 + 1.054(TE_{111})$ $+ 3.01 \times 10^{-3}(TE_{111})^2$	$T_{LL} = -40.1 + 2.03(TE_{110})$ $+ 3.86 \times 10^{-3}(TE_{110})^2$
Lead shield (5/9/72-6/9/72)	Upper	$T_{UU} = -5.78 + 1.34(TE_{113})$ $+ 1.12 \times 10^{-3}(TE_{113})^2$	$T_{UL} = -16.3 + 1.67(TE_{112})$
	Lower	T_{LU} (not operating)	$T_{LL} = -30.6 + 1.88(TE_{110})$ $+ 3.67 \times 10^{-3}(TE_{110})^2$

^aNumbers in parentheses identify the thermocouple used in the correlation. Refer to Fig. 1 (p. 4) for location.

APPENDIX I. GAS RELEASE AND BURNUP CALCULATIONS

APPENDIX I. GAS RELEASE AND BURNUP CALCULATIONS

The gas release was calculated from the measured pressure changes reported in Fig. 9, pp. 14, 15, 16, and 17. To enable us to make these calculations we determined the free volume available to gases inside the fuel pin and pressure-measuring system before sealing the system. This volume was determined by attaching a known pressurized standard volume system containing a calibrated pressure gage and measuring the pressure change caused by opening a valve between the two systems. To estimate the volume of various portions of the internal gas system (needed for use in differential gas release calculations) we made calculations based on detailed dimensions of the parts. The total for all three portions, shown in Fig. 1-1, was 3.4 cm³, compared to a value of 3.39 cm³ determined by the technique described above.

The calculation used for the total gas release is given below:

$$AGR \text{ (atoms gas released)} = V(\Delta P)(N)/RT ,$$

where

V = total volume of the gas system,

ΔP = pressure change at zero power from November 22, 1971 to June 9, 1972,

N = Avagadro's number,

R = gas constant, and

T = temperature at zero power.

$$AGR = \frac{(3.39 \text{ cm}^3)(4.22 \text{ atm})(6.023 \times 10^{23} \text{ atoms/mole})}{(82.05 \text{ cm}^3\text{-atm/}^\circ\text{K-mole})(328^\circ\text{K})}$$

$$= 3.20 \times 10^{20} \text{ atoms.}$$

Fig. I-1. Schematic of Fuel Element Pressure Measuring System.

$$AGG \text{ (atoms gas generated)} = \frac{(\text{energy released})(\text{inert gas yield/fission})(N)}{(\text{energy released/fission})}$$

$$= \frac{(15783 \text{ kWhr})(0.32 \frac{\text{g-atoms of inert gas}}{\text{g-atom fissioned}})(6.023 \times 10^{23})}{(5.3 \times 10^6 \text{ kWhr/g-atom fissioned})}$$

$$= 5.74 \times 10^{20} \text{ atoms.}$$

$$\% \text{ gas released} = \frac{3.19 \times 10^{20}}{5.74 \times 10^{20}} \times 100\%$$

$$= 56\%$$

The differential gas release at power was calculated as follows:

$$AGR = \left(\frac{V_L}{T_L} + \frac{V_P}{T_P} + \frac{V_S}{T_S} \right) \frac{\Delta P(N)}{R},$$

where

V_L , V_P , and V_S = partial volumes shown in Fig. I-1,

T_L , T_P , and T_S = average temperatures of the three volumes V_L , V_P ,
and V_S

ΔP = pressure change over time interval at power, and

R = gas constant.

At 14 kW/ft from November 22, 1971 to May 8, 1972:

$$\Delta P = 6.0 \text{ psi} = 0.41 \text{ atm}$$

$$AGR = \left\{ \frac{0.2 \text{ cm}^3}{1000^\circ\text{K}} + \frac{2.4 \text{ cm}^3}{475^\circ\text{K}} + \frac{0.8 \text{ cm}^3}{375^\circ\text{K}} \right\} \frac{(0.418 \text{ atm})(6.023 \times 10^{23} \text{ atoms/mole})}{(82.05 \text{ cm}^3 \text{ atm/}^\circ\text{K-mole})}$$

$$= 2.2 \times 10^{19} \text{ atoms.}$$

energy release* = 1680 kWhr (6 1/4 days at 14 kW/ft for 9.6-in. fuel column)

$$AGG = \frac{(1680 \text{ kWhr}) \left(0.32 \frac{\text{g-atoms inert gas}}{\text{g-atom fissioned}} \right) (6.023 \times 10^{23})}{(5.3 \times 10^6 \text{ kWhr/g-atom fissioned})}$$

$$= 6.11 \times 10^{19} \text{ atoms.}$$

$$\% \text{ release} = \frac{2.21 \times 10^{19}}{6.11 \times 10^{19}} \times 100\%$$

$$= 36\%.$$

The volume changes caused by swelling of the fuel column and cladding were considered negligible since the volume in this hot section is a minor part of the total volume (<6%).

*Assumes that the average power over the time interval is approximately equal to the midplane power.

The average burnup was estimated by assuming that the axially integrated burnup over the life of the test was approximated by the midplane burnup value. This assumption is based on results from an earlier experiment (P7 capsule) that operated in a similar location and was controlled in a similar manner. Flux monitor wires attached to the capsule wall in P7 yielded the curve presented in Fig. I-2. The relative position of our fuel element and the estimated flux curve (neglecting end effect) are also shown in this figure. It can be seen that the relative flux value at the midplane of the fuel element is approximately 0.98. This compares quite well with the average value of 0.96 estimated over the length of the entire fuel element. The midplane burnup was calculated from operating data presented in Fig. 9, pp. 14, 15, 16, and 17, using the following equations:

$$\begin{aligned} \text{Burnup} &= \frac{(\text{power generated}) \times 100}{(\text{power/fission})(\text{heavy metal initially present})} \\ &= \frac{(15783 \text{ kWhr})(235 \text{ g fissioned/g-atom fissioned}) \times 100}{(5.3 \times 10^6 \text{ kWhr/g-atom fissioned})(40.7 \text{ g U + Pu})} \\ &= 1.7\% \text{ FIMA.} \end{aligned}$$

Fig. I-2. MINT-1 Flux Distribution.