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PLASTIC STRAIN IN THIN FUEL ELEMENT CLADDING DUE TO UO_2 THERMAL EXPANSION

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July 7, 1961

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PLASTIC STRAIN IN THIN FUEL ELEMENT CLADDING

DUE TO UO_2 THERMAL EXPANSION

I. ABSTRACT

The results are presented of short time, high heat flux capsule irradiations performed in GETR Trail Cable Facility to determine the magnitude of plastic strain induced in the capsule cladding due to UO_2 thermal expansion. Annular geometry capsules were employed with both internal and external cladding and forced convection cooling of both surfaces to simulate the reference superheat fuel element design. Both 304 stainless steel and 3003 aluminum claddings of various thickness were used to determine the influence of cladding strength. The initial gap spacing was purposely varied as an additional parameter. The program was undertaken as a part of the effort to evaluate plastic strain cycling as life limitation in the use of thin fuel element cladding. An over-all summary of the experimental results is given in Table I.

TABLE I

CAPSULE INITIAL FABRICATION PARAMETERS AND OBSERVED "AVERAGE" OUTSIDE DIAMETER GROWTH

Capsule No.	Clad Material	Clad Thickness in.	Nominal Initial Diametral Gap in.	Measured Outside Diametral Gap in.	Measured Inside Diametral Gap mils	Capsule Operating "Average" Surface Heat Flux, BTU/hr-ft ²	Observed "Average" Outside Diameter Growth in.
TR-1	Al	.049	.003	.0053	4.9	160,000	.0061
-2	Al	.049	.003	.0048	3.3	309,000	.0089
-3	Al	.049	.009	.0105	10.2	585,000	.0039
-4	Al	.049	Zero Swaged	.0016	4.5	350,000	.0060
-5	Al	.028	.006	.0075	6.4	350,000	.0042
-6	Al	.016	.003	.0100	3.4	220,000	.0021
-7	Al	.016	Poor Data				
-8	Al	.010	Poor Data				
-9	Al	.010	Poor Data				
-10	Al	.010	Poor Data				
-11	Al	.049	.009	.0111	11.4	350,000/	.0025
-12	Al	.049	Lead-Filled Dummy				
-13	Al	.049	Zero Swaged	.0006	0.3	426,000	.0021
-14	Al	.010	Poor Data				
-15	S.S.	.049	Zero Swaged	.0001	3.7	>350,000	.0026
-16	S.S.	.028	Zero Swaged	.0000	5.9	397,000	.0016
-17	S.S.	.016	Zero Swaged	.0000	2.0	397,000	.0046
-18	S.S.	.012	Zero Swaged	.0018	9.0	359,000	.0030
-19	S.S.	.028	Zero Hydroformed	.0043	2.0	326,000	.0032
-20	S.S.	.016	Zero Hydroformed	.0019	0.7	334,000	.0106
-21	S.S.	.028	Zero Hydroformed	.0053	2.7	344,000	.0028
-22	S.S.	.016	Zero Hydroformed	.0001	2.3	358,000	.0037
-23	S.S.	.028	Arc-Fused Powder			Not yet run	
-24	S.S.	.016	Arc-Fused Powder			Not yet run	
-25	Al	.049	Zero Swaged	.0006	8.4	378,000	.0055
-26	Al	.049	.003	.0050	7.5	304,000	.0022
-27	Al	.049	.009	.0096	11.8	369,000	.0015
-28	Al	.028	Zero Swaged	.0012	9.2	348,000	.0055
-29	Al	.028	.003	.0039	8.8	347,000	.0041
-30	S.S.	.049	Zero Swaged	.0041	3.2	300,500	.0000
-31	S.S.	.028	Zero Swaged	.0016	6.7	367,500	.0020
-32	S.S.	.016	Zero Swaged	.0005	9.2	360,500	.0018
-33	Al	.028	.009	.0090	8.1	329,000	.0002
-34	S.S.	.049	.003	.0056	13.4	332,000	.0008
-35	S.S.	.049	.009	.0111	9.8	344,000	.0000
-36	S.S.	.028	.003	.0040	9.2	385,500	.0037
-37	S.S.	.028	.009	.0102	9.0	376,000	.0002
-38	S.S.	.016	.003	.0021	11.7	374,000	.0041
-39	S.S.	.016	.009	.0096	14.9	343,000	.0022

II. SUMMARY

A total of 36 fuel bearing capsules have been irradiated and examined to date in the program with the following generalized results:

1. The diameter of the capsule external cladding increased significantly as a result of irradiation for almost every capsule.
2. The over-all length of the capsules increased with only one or two exceptions and the length increase was found to vary in a consistent pattern around the periphery of the capsule.
3. No significant change was observed in the diameter of capsule internal cladding with one possible exception.

Analysis of the external cladding dimensional changes has shown the magnitude of the change to be a function of the restraining forces imposed on the UO_2 by the clad as well as a function of the capsule heat generation and the initial pellet-cladding gap. These functional relationships are stated in general terms as follows:

1. The diameter change, or growth, decreases with increased cladding strength as shown in Figure 43.
2. The diameter change increases essentially linearly with increasing capsule heat generation as shown in Figure 32.
3. The diameter change decreases somewhat with increased initial pellet-cladding gaps as shown in Figure 40. However, the UO_2 appears to thermally expand sufficiently to close any of the initial gaps within the range studied - 0 to 11 mils - and produce clad growth.
4. For the particular capsule configuration and operating conditions employed in these tests, the maximum expected outside diameter increase is approximately 10 mils, equivalent to 0.8% total strain.

The plastic straining of the cladding observed as the result of a single cycle of irradiation in these tests will probably be cyclic with changes in power generation when the cladding is non-free standing under the existing external pressure. It was experimentally determined that the UO_2 shrinks back to approximately its original dimensions when power generation ceases.

Analysis of the observed capsule length changes has not been completed. The changes in length appear to be the result of action of the pellets against the adjacent cladding rather than direct axial expansion since changes in the initial axial gap did not significantly affect the increase in length. The length increases varied sinusoidally around capsule periphery, indicating that the relatively heavy end plugs were tilting with respect to each other, probably as a result of circumferentially non-uniform heat generation within the capsule.

Relatively large amounts of gas - 6×10^{-2} cc/gm - were found to evolve during irradiation from the conventionally processed, sintered UO_2 pellets used in the initial capsules. By modifying the capsule design, and improving the capsule fabrication procedure, the magnitude of the gas evolved in subsequent capsules was reduced significantly and internal gas pressure eliminated as a possible contributor to the observed cladding growths. Comparison of subsequent growth results with those obtained previously indicated several cases where internal gas pressure was probably a factor. These capsules were not considered in data analyses or in forming the experimental conclusions.

No difference was observed within the experimental error between swaged and unswaged capsules in producing outside cladding growth other than that attributable to generally smaller initial gaps present in swaged capsules.

New equipment was designed and built and a completely new irradiation technique developed to permit the rapid conduct of these capsule irradiations in the GEIR Trail Cable Facility and the post-irradiation dimensional measurements in the GEIR canal.

III. CONCLUSIONS

Both circumferential and axial plastic strains were produced in thin fuel element cladding as a result of UO_2 thermal expansion during irradiation. Evidence was obtained that the circumferential cladding plastic strain will be cyclic with changes in the fuel element power when the cladding is non-self supporting under the external pressure environment.

Calculations have been made to indicate the life to failure from plastic strain cycling of a fuel element cladding experiencing circumferential strains of the order observed in these tests. Using the Coffin relation and available property data on 304 stainless steel at approximately 1200 °F, the results predict a life in excess of 1000 complete strain cycles. This compares with a maximum of 500 full power cycles expected during actual superheat fuel element life. The quantitative significance of the above result is severely limited by at least the following qualifications:

1. The circumferential strain may not be the most severe repetitive clad strain.
2. The magnitude of the plastic strain observed in these room temperature tests may become appreciably larger at superheat operating temperatures.
3. The strain cycle behavior of 304 stainless steel may be unfavorably altered by environmental factors such as irradiation, steam corrosion, low frequency cycling, etc.

The above result can, at most, only be considered encouraging; and a definite conclusion concerning the strain cycle life limitation must await more extensive evaluation of the behavior of 304 stainless steel followed by actual operation of prototype superheat elements for a total number of cycles in excess of that expected during the fuel element life. The maximum number of power cycles experienced by one of the SADE loop test elements to date is 55.

The consequences of the observed axial cladding strain cannot be evaluated because it is uncertain whether the strain is localized or uniform along the clad length and because it is not known if the strain will be cyclic. If both cyclic and highly localized, the axial strain could be more significant as a failure mechanism than the circumferential. The axial strain observed in full length SADE elements has been of the same order as observed in these capsule tests.

Significant quantities of gas were found to be evolved from conventionally fabricated UO_2 sintered pellets. Gas, in this amount, has serious consequences with regard to the long-term pressure buildup within the element. Inclusion of an evacuation and heating step in the capsule fabrication procedure affected a sevenfold reduction in the gas evolved during irradiation.

Both the pellet gas release described above and the fact of UO_2 thermal expansion itself, separately and together, have important implications with respect to the internal heat transfer characteristics of the annular element. Future calculations should be modified to account for the considerably improved heat transfer path to the outside surface due to high UO_2 clad interference pressures and the poorer heat transfer path to the inside surface due to both a larger gap and lower gas conductivity. This effect has been partially evaluated for the purpose of analyzing the capsule growth data. A significant shift may result in the heat flow split between inner and outer clads.

IV. RECOMMENDATIONS

Most of the recommendations arising from the results of these experiments are already incorporated into existing development programs in support of thin clad, superheat reactor fuel. These recommendations are:

1. Experimental determination of the effect of irradiation, relaxation under load and superheat temperatures (900 °F - 1300 °F) on the strain cycle behavior of 304 stainless steel.
2. Accumulation of a total number of full power cycles beyond that expected during the actual superheat fuel element life using thin clad, superheat fuel elements operating at superheat conditions.
3. Addition of evacuation and heating steps in the manufacture of thin clad fuel to reduce pellet gas evolution.
4. Modification of the heat transfer calculation methods for the annular geometry fuel element to account more realistically for the observed internal effects.

V. INTRODUCTION

This program of capsule irradiations was undertaken as part of an effort to evaluate plastic strain cycling as a life limitation in the use of thin clad fuel elements in a superheat reactor environment. Other phases in the evaluation include experimental determinations of the effects of irradiation, cycling rate and relaxation under load, and superheat temperatures on the behavior of stainless steel. Eventually, actual power cycling of thin clad fuel elements at superheat conditions will be undertaken. This work is being performed under the Atomic Power Equipment Department Superheat Research and Development Contract with the United States Atomic Energy Commission.

Metallurgical requirements for superheat conditions dictate the use of an intermediate cross-section clad material such as stainless steel. To provide reasonable neutron economy in a thermal spectrum reactor, the cladding must be maintained as thin as possible. The concern for plastic strain cycling as a mode of fuel element failure in using thin cladding arises from three interrelated effects: the thin clad, the external pressure, and the thermal expansion of the UO_2 fuel. In the 1000 psi steam pressure environment of a superheat reactor, the desired thin cladding will be deformed plastically until it is in tight contact with the underlying UO_2 and thereafter, constrained to follow any movement of the UO_2 . As the UO_2 thermally expands and contracts in response to internal heat generation changes during operation, the UO_2 movement may be sufficient to carry the clad repeatedly through reversed cycles of plastic strain. If the magnitude of the plastic strain range is large enough, fatigue failure of cladding could result within a relatively short number of power cycles.

VI. EXPERIMENTAL APPROACH

From the standpoint of obtaining information most directly applicable to the plastic strain cycle mechanism, tests involving fuel elements operating at superheat conditions would have been most desirable. However, the only available facility was the SADE Loop. As a result, the number of tests that could be performed was very limited and each relatively expensive. There was the additional complication that the investigation could well require in-core measurements. For example, if the UO_2 grows during operation but returns to nearly identical dimensions after shutdown, then changes in the cladding would be essentially undetectable by pre- and post-irradiation measurements. The method of operation of the VBWR is such that operating pressure is obtained before, and persists after, actual power generation in the core. Thus, the cladding would be shrunk back over the pellets before the element could be removed for examination.

As an alternative approach, it was decided to conduct the investigation in several phases. In the first step, the magnitude of the cladding strain produced by a single cycle of irradiation at high heat flux and in the absence of external pressure would be determined. To facilitate the irradiations, the experiments would be conducted with relatively low cladding temperatures using the GETR Trail Cable irradiation facility. In order to make the results from these tests applicable to superheat conditions, the experiment was designed to provide data such that relationships could be obtained between the magnitude of the cladding strain and the clad strength, initial gap, and heat generation level. With these relationships established, it appeared feasible to predict the clad strain to be experienced at superheat temperature, taking into account changes in clad strength, gap spacing, and UO_2 thermal expansion in reaching superheat conditions.

In the second phase of the program, the extent that the cladding plastic strain would be cyclic with changes in heat generation was to be determined. Irradiated capsules from phase one above were to be externally pressurized in excess of the clad strength and the amount of clad shrinkage measured. These measurements would indicate the percentage of the initial clad strain that could be reversed when the fuel element power generation ceased and also define the strain range for subsequent power generation cycles.

The information from the above two phases of the program, coupled with data from the other phases on the strain-cycle behavior of stainless steel mentioned previously, would provide the basis for predicting the cladding life with respect to plastic strain cycling at superheat conditions. The results of this life prediction would eventually determine the amount of effort required to test actual thin clad fuel elements under extended power cycling at superheat conditions.

The purpose of this report is to present the experimental results of the initial two phases discussed above. To recapitulate, the specific objectives of these two phases were:

1. To determine the amount of clad strain produced by a single cycle of UO_2 power generation as a function of the magnitude of the power generation, the initial clad to pellet gap, and the clad strength.
2. To determine the extent to which the observed cladding strain will be repetitive in subsequent power generation cycles.

VII. EXPERIMENTAL FACILITY AND SUPPORTING TEST EQUIPMENT

A. GETR Trail Cable Facility

The GETR Trail Cable Facility was selected for these capsule irradiations after brief consideration of the GETR hydraulic rabbit. The rabbit tube is unsatisfactory for high heat generation capsules due to the complete coolant flow reversal required at the peak heating position in order to extract the capsule. The use of the Trail Cable Facility permits continuous coolant flow in the same direction during capsule insertion, irradiation, and removal.

The GETR Trail Cable Facility is a dead end tube extending from a 45° angled port opening in the third floor down through the reactor concrete shielding and reactor pool to a point 3" below the bottom of the core as shown in Figure 1. The tube is vertical and directly against the reactor vessel wall from below the core to several feet above. The tube is filled with stagnant water to the same level as the reactor pool through several inter-connecting 1/2" weep holes located at the knee of the tube as it bends away from the reactor vessel. The bottom end of the tube is fitted into the GETR capsule coolant header and enclosed in a jacket that extends above the top of the core. Capsule cooling water flows through the annulus between the jacket and the tube to provide some cooling, but the arrangement is inadequate for high heat generation capsules. The peak neutron flux in the tube is between 5×10^{13} and 1×10^{14} n/cm²-sec depending on the location of other experiments and control rod position.

The primary advantages in using the facility are direct access to the neutron flux zone without intervening seals and the capability of adjusting the irradiation intensity by vertical movement within the tube. The only serious disadvantage involved is the necessity of transferring the irradiated material from the port opening to the canal without benefit of water shielding, a distance of approximately 12 feet.

B. Capsule Irradiation System

The system devised for performing the capsule irradiations consisted of the following functional components:

1. A capsule holder to enclose the capsules during irradiation and properly direct cooling water flow over the capsule surface to insure adequate cooling.
2. A 50-foot length of flexible polyethylene pipe attached to the capsule holder, to permit manual insertion, positioning, and removal of the capsule from the facility tube and to conduct cooling water from the cooling water supply system to the capsule holder.
3. A cooling water supply system to provide demineralized water at nominally 20 gpm and at less than 100 °F inlet temperature to the flexible polyethylene pipe and to permit accurate measurement of the water flow.
4. An instrumentation system to accurately measure and visually indicate the cooling water temperature rise - nominally 6 °F - across the capsule.

The governing specification in the design of the irradiation system was the GETR license limitation of 220 °F maximum surface temperature for capsules irradiated in reactor pool positions. The maximum water inlet temperature, cooling water flow rate, and the consequent small water temperature rise were all dictated by this requirement.

1. Capsule Holder Description

A drawing of the capsule holder initially designed for these experiments is shown in Figure 2. The material of construction was entirely 1100 Al, with the exception of the lock pin, spring and safety cable, to minimize activation and subsequent handling problems. The water inlet end of the capsule holder is an adaptation of an ordinary ferrule type tubing fitting for attachment to the flexible polyethylene pipe. The lock pin arrangement was chosen to permit remote removal of the holder shroud to unload the irradiated capsules. Reloading of unirradiated capsules was performed directly using channel lock pliers for handling. Spacer pins on the inside of the shroud provided for lateral positioning of the capsule. The compression spring supplied 5 pounds force to seal the capsule end plug against the circular seat and to hold the shroud against the lock pin during irradiation. A 40-mesh aluminum screen was placed over the outlet water opening to trap any fuel fragments released in case of an element failure. Inlet and outlet thermocouple locations are indicated in the drawing. Figure 3 is a photograph of the sample holder assembled and disassembled along with a dummy fuel capsule.

Cooling water flow passes down through the inside cladding, is reversed, and passes up through the annulus between the outside clad and the shroud and finally exhausts into the facility tube at right angles to the capsule holder axis. The exhaust flow direction eliminates reaction forces that would affect the capsule position. The cooling water flow passages were designed to provide 15 ft/sec water velocity and approximately 5000 BTU/hr-ft²-°F film coefficient on both the inside and outside cladding at 20 gpm.

In the course of the initial ten capsule irradiations, it became evident that the initial capsule holder design was unsatisfactory due to non-uniform circumferential heating of the capsule or poor water flow distribution or a combination of both. An accurate measurement of the bulk average exit water temperature was not being obtained. A new capsule holder was designed and built to correct this problem as shown in Figure 4 .

The changes introduced to insure more uniform flow are an increase in the number of spacer pins in the outer annulus from three at 120° spacing to four, 90° apart, and an increase in the length of the pins so that radial movement of the capsules is limited to .015" from the capsule center line. In addition, the lower capsule support was changed to a solid aluminum piece with a definite flow area rather than requiring the flow to pass through the potentially non-uniform opening between the compression spring coils. To alleviate the effect of non-uniform heating on the measurement of the capsule water temperature rise, the flow direction through the capsule was reversed. The inlet water first passes down the relatively narrow annulus on the outside of the capsule where the effect of non-uniform heating is manifested most severely. Water from this pass undergoes appreciable mixing as it turns to enter the second pass and flows up the larger inside annulus where there is a better opportunity for cross flow and mixing. At the outlet end of the second pass, a mixing chamber was provided to further reduce the water temperature non-uniformity before it passes out the side outlets and contacts the outlet temperature thermocouples.

At this same time, the capsule holder was adapted to underwater reloading to permit irradiation of previously irradiated capsules and to reduce the delay required between capsule irradiations for decay of the capsule holder activity. The use of a nut threaded onto the central support rod to hold the end closure in place accomplished this objective. The central support rod material was changed to stainless steel for this purpose. A special tool was built to thread the nut on and off under water. The redesigned capsule holder was used for the final twenty-seven capsules irradiated with no difficulty in unloading and loading the capsules under water. A substantial improvement in the accuracy of the water temperature differential measurement was obtained by the combination of the capsule redesign and changes in the instrumentation system discussed below.

2. Flexible Polyethylene Pipe

This pipe was selected in order to provide the flexibility required to negotiate the bends in the Trail Cable Facility tube while retaining the strength and stiffness necessary for inserting and withdrawing the capsule holder through

the 30-foot length of the facility. The pipe was 3/4" nominal with a 1.050" outside diameter and 0.840" inside diameter. The choice of pipe size was based on a balance between flexibility and allowable pressure drop. Calculations indicated that the polyethylene would be satisfactory from a radiation damage standpoint for the short irradiations desired. A slight stiffening of polyethylene immediately above the capsule holder was the only detectable effect in the course of seventeen capsule irradiations.

The pipe length, measured from the tip of the capsule holder, was marked on the pipe at intervals to provide positioning information during the capsule irradiations. The thermocouple extension leads from the capsule holder were also simply plastic taped to the pipe at intervals. A quick disconnect fitting was used on the water inlet end of the pipe to mate to the outlet from the cooling water supply system.

3. Cooling Water Supply System

The cooling water system, as initially built, was a closed loop recirculating system using reactor pool water and is shown schematically in Figure 5 .

The pool water was withdrawn through a 1-1/2" diameter rubber suction hose and foot valve extended under the reactor missile shield and down into the reactor pool to a depth of 3 to 4 feet. A centrifugal pump provided the suction lift and pressure head for the system flow. From the outlet of the pump the water passed through a flow control valve, through a heat exchanger and then through a 1/2% accuracy, orifice plate flow meter. The function of the heat exchanger was to reduce the normally 120 °F pool water to less than 100 °F in order to provide a lower sink temperature for capsule heat transfer; thereby, reducing the capsule surface temperature. All of the above equipment was mounted on a skid and interconnected with standard steel pipe fittings as shown in Figure 6. The water from the flow meter outlet passed through the polyethylene pipe and the capsule holder and then back up the facility tube to the weep holes and out into the reactor pool, completing the circuit.

Specifications on the capsule cooling system equipment were as follows:

1. Pump - Deming Self Priming Centrifugal Pump, 20 gpm at 110 foot head, cast iron casing and impeller; 2 hp, 3450 rpm motor.
2. Heat Exchanger - Graham Heliflow Model No. 9XS-14S, 9.63 sq. ft., 200,000 BTU/hr duty, carbon steel tubes and cast iron case.
3. Flowmeter - Barton Model 227 Differential Pressure Indicator, 0-30 gpm sq. root scale. Model 158 orifice plate for 200" of water differential pressure at 30 gpm; 1/2% accuracy calibration; Model 157 orifice flanges.

After approximately one half the capsule irradiations were completed, the cooling water supply system was changed to use demineralized water directly from the reactor makeup supply. The continuous flow availability of this water was limited but its 65 °F inlet temperature provided an additional margin on the capsule maximum surface temperature. The flowmeter was removed from equipment skid and mounted directly on the demineralized water supply line.

4. Instrumentation System

The cooling water temperature rise measurement from the capsule instrumentation system coupled with the water flow measurement indicates the total capsule heat generation - nominally 17 kw thermal - during irradiation. The basic system employed for the temperature rise measurement consisted of two independent pairs of "bucking" thermocouples as the primary sensing elements, a fixed gain amplifier to boost the differential thermocouple signal, a voltage divider to match the amplifier output to the recorder range, and a recorder to visually indicate and record the measurement directly in °F.

The use of bucking thermocouples with zero offset compensation should provide an ultimate realizable accuracy of about 1/4% in measurement of the water ΔT since the method depends on reproducibility of the thermocouple emf vs. temperature relation over a very narrow temperature range, rather than on the absolute accuracy of thermocouple emf's relative to the reference junction temperature. The accuracy attained in actual practice depends on the quality of the instrumentation and how representative the water temperature, at the thermocouple, is of the bulk average water temperature.

The thermocouples initially employed were 1100 Al sheathed; MgO insulated, chromel-alumel wire, grounded to the sheath at temperature sensing point. Successive difficulties were encountered with these thermocouples due to water leakage, high AC noise pickup, and from gamma heating after the thermocouples were electrically and thermally insulated from the sheath to correct the noise pickup. Finally, ordinary, plastic insulated, chromel-alumel extension wire was used for the thermocouples with quite satisfactory results. The bare junctions of these couples were immersed directly in the inlet and outlet water. The thermocouples were kept carefully insulated from the sample holder body and performed adequately with respect to AC noise pickup provided the leakage resistance path to the holder was greater than about 3000 ohms with full water flow through the sample holder. Three independent pairs of couples were installed in each sample holder. One couple of each pair was installed in the inlet flow stream and the remaining couple in one of the three outlet water passages. Two of the pairs were for normal use with the third pair as a backup.

The differential output of the thermocouples is 23μ -volts for a 1°F water temperature difference. The usual operating ΔT was 6 °F.

Output from the two operating thermocouples was fed through a pair of selector switches to each of the two instrument channel amplifiers. The selector switch was arranged to permit the measurement of each individual thermocouple output and each of the four possible differential pair outputs on each instrument channel.

The signal amplifiers used initially were Kintel Model 204 DC Galvanometers. These amplifiers were adjusted normally to provide a signal gain of 1000. A zero offset compensation control permitted balancing of differential couple pairs differing in output by 15μ -volts. A meter on the amplifier provided a direct reading of the thermocouple signal in μ -volts. The Model 204

amplifiers were replaced by Kintel Model 114C Differential DC Amplifiers for the last seventeen capsule irradiations with a resulting substantial improvement in signal-to-noise ratio.

The capsule ΔT indicator and recorder was a Minneapolis-Honeywell two pen recorder with 1 sec response and 0-10 mv full scale range on each pen. The output signal from the amplifiers was fed through a voltage divider network selected to make the recorder direct reading in $^{\circ}\text{F}$ with a full scale range of 10 $^{\circ}\text{F}$.

The instrumentation system components were housed in an instrument cubicle located adjacent to the facility tube inlet port on the GETR third floor. The capsule irradiations were controlled by direct observation of capsule water temperature rise measurements on the recorder charts. The recorder response to vertical position changes of the capsule in the irradiation zone was essentially instantaneous and temperature equilibrium was established within 10 seconds of each discrete movement.

During the final seventeen capsule irradiations, with the instrumentation system in its final form described above, the maximum deviation of the average value of the two independent heat generation measurements from the desired capsule heat generation was less than 14% and, in all but two instances, less than 8%. The maximum deviation between the two independent heat generation measurements was 30% and always bracketed the desired heat generation value. This latter deviation is probably attributable mainly to lack of complete mixing of the outlet water before reading the outlet thermocouples.

5. Operational Procedure

The capsule irradiation procedure was quite straightforward and required less than fifteen minutes to perform after the capsule holder was loaded. The capsule holder was inserted into the facility tube to a depth of 20 feet and then cooling water flow established. Air was bled out of the flowmeter piping and the flow rate adjusted to exactly 20 gpm. The thermocouples were connected to the instrument cubicle and each thermocouple output checked. The instrumentation system was left on continuously to minimize drift due to warmup. The capsule holder was then lowered to a depth of 28 feet, the thermocouples switched to differential output, and the signal from each thermocouple pair adjusted to exactly zero as indicated by the recorder pens. The capsule holder was then lowered directly into the flux zone until the indicated temperature differential on the recorder was 6 $^{\circ}\text{F}$.

The capsules remained in the peak heating position approximately 5 minutes. As a further check on the actual capsule heat generation, the cooling water flow was varied in discrete steps during the irradiation from the maximum available flow to a minimum flow of 13 gpm. The flow rates were noted on the recorder chart adjacent to the indicated ΔT . Figure 7 is the recorder chart from a capsule irradiation following this procedure. After the irradiation, the indicated ΔT was plotted against the flow rate and the slope of the resulting curve used to calculate the actual capsule heat generation.

After completing the irradiation, the capsule was withdrawn from the flux zone up to a depth of 20 feet and allowed to decay for 24 hours before transfer to the canal. Cooling water flow was continued for 15 minutes following withdrawal from the flux zone. The combined capsule and capsule holder dose rate after 1 day's decay was 0.5-1 R/hr at 6 feet. Near the end of the program, a transfer cask became available for use with the Trail Cable Facility and permitted the capsule to be transferred to the canal and unloaded after 1 hour's decay. The use of this cask allowed the final seventeen capsules to be irradiated at the rate of five/day.

C. Dimensional Measurement Equipment

Special equipment was designed and built to permit dimensional measurements on the capsules immediately after irradiation under water in the GETR canal. The objectives were to minimize the waiting time and the expenses associated with shipping the capsules to the RML for measurement and to reduce the physical handling of the capsules to a minimum prior to measurement. Following irradiation, the capsules were unloaded from the capsule holder directly onto the underwater tray where the measurements were made. The same equipment was employed for both pre- and post-irradiation measurements.

The equipment initially built and employed for measurements on the initial twenty capsules is shown in Figure 8. The equipment consisted of a jig to locate the measurement points relative to the capsule and three individual tools to perform the O.D., I.D., and length measurements. The jig provided for seven discrete measurement points along the length of the capsule for both inside and outside diameter. The location of these points relative to the capsule internals is shown in Figure 9. By rotating the capsule about its axis, it was possible to obtain measurements at discrete radial orientations.

The practice adopted in taking the measurements was to make the seven O.D. measurements at 0° orientation and seven more at a 90° radial orientation from the first. The seven I.D. measurements were taken at the 90° orientation and then the length was measured a total of eight points, one on the inside cladding and one on the outside cladding at each 90° circumferential displacement. The radial orientations were indicated by paint markings at one end of the capsule, and this end was taken as the zero reference end for O.D. and I.D. measurements along the capsule length. The capsule was always loaded into the capsule holder painted end first, so that this end was up with respect to the core during irradiation and the opposite end entered the flux zone first. These conventions provided a means of detecting any influence on growth of axial flux distribution along the length of the capsule. No special provisions were made to orient the capsule radially with respect to the core.

The individual measurement tools were simply ordinary micrometers adapted for operation by long flexible cables and mounted on fixtures compatible with locating jig. The O.D. measurements were taken with Starrett 1-2 inch micrometer mounted with the plane of the bridge vertical and the barrel rotated 90° to permit reading from above. The micrometer was graduated to .001" with a vernier to permit reading to .0001". The barrel rotation introduced a constant 5 mil error in all the O.D. measurements and was taken into account in subsequent analyses. The I.D. measurements were taken with the appropriate one of two Brown and Sharpe Tri-Point Intramiks covering the ranges 0.600 to 0.700" and 0.700 to 0.800" respectively. The smallest scale division on these micrometers is .0002". The mounting fixtures for the I.D. and O.D. micrometers moved axially with respect to the capsule on two aluminum rods. Projections on the fixtures engaged with notches cut in the rod to locate the discrete axial measurement points. The reproducibility of the individual O.D. measurements was ± 0.5 mils and the I.D. measurements ± 0.8 mils, provided the capsule cladding was sufficiently strong that it did not deflect under the micrometer loading. The micrometer loading was actually quite low due to the torque limiting characteristics of the flexible cables employed.

Capsule length measurements were taken with a 5 to 6" micrometer attached to an aluminum plate mounted in a horizontal plane parallel to the axis of the capsule. Initially, the length measurements were taken between the two cladding weld beads at each end of the capsules; one measurement on the outside clad and one on the inside. When difficulty was experienced in interpreting the length measurements, the micrometer was modified to make a single length measurement between the recessed faces of the capsule end plugs. The modification consisted of reducing the diameter of both the stationery and movable anvils and extending the stationery anvil length $3/16$ " while reducing the movable anvil length to maintain a constant measurement span. The smallest scale division on the length micrometer was .001" and the reproducibility of the length measurements about $\pm .002$ ". The accuracy of the length measurements was restricted more by limitations in reproducing the exact radial orientation of the capsules than the capabilities of the measurement equipment itself.

The above described equipment performed quite satisfactorily in terms of accuracy and was employed for the initial twenty capsules in the program. However, its use for underwater measurements was quite tedious. About two hours, minimum, were required for the actual measurements plus an additional half hour of setup and cleanup time. Further, despite an initial lubrication with Vaseline and care in drying after each use, the force required for operation was increasing due to corrosion. Consequently, a new set of equipment was built employing dial gages as the indicating device. This equipment, along with associated measurements jig, is shown in Figure 10. The O.D. measurement tool is essentially a pair of outside calipers with a dial gage to indicate the amount of caliper opening. The "calipers" were mounted on an eight foot long extension and a steel cable attached to the movable arm to enable the arms to be opened. The dial gage spring plus a light spring over the dial gage probe and sleeve provided the force to close the jaws over the capsule to be measured. The dial gage range for this tool was 0 to 0.2" and the minimum scale division .0001".

A short cylindrical extension on the stationery jaw of the caliper mated with rectangular slots in the base of the jig to locate the caliper axially with respect to the capsule. The number of measurement points along the capsule axis was increased to 10, evenly spaced.

Length measurements were taken between a fixed reference point mounted on the base of the jig and a lever-operated dial gage also rigidly mounted to the base. To obtain a measurement, the dial gage probe was fully retracted using the lever, the capsule slipped in between the probe and reference point, and then moved horizontally until in tight contact with the fixed reference point. The dial gage probe was then allowed to extend until in contact with the opposite end of the capsule and the length reading determined. Both the dial gage probe and the fixed reference point contacted the recessed face of the capsule end plug. The dial gage range was 0 to 0.4" with a minimum scale division of 0.0001".

A reference standard for both O.D. and length measurements was built for checking the dial gage calibrations before and after each set of capsule measurements. The dial gage equipment was used for measurements on the last seventeen capsules without any detectable change in calibration.

Duplicate sets of measurements were taken on two capsules using both the old and new measurement equipment. Figs. 11 and 12 are a comparison of the results obtained with each set of equipment on capsule TR-32. The new equipment was found to read on the average 0.5 mil less than old equipment. Taking this constant difference into account, the maximum deviation between the capsule average outside diameters, as determined by the two sets of measurements, was 0.9 mil. The new equipment provided a lower, and probably more correct, value for the O.D. in all cases.

Capsule measurements were performed on a tray suspended from the GETR canal bridge as shown in Figure 13. The tray immersion depth under water was adjustable to a maximum of eight feet. Four feet immersion was usually sufficient to reduce the radiation dose from the capsules to less than the prevailing background. Micrometer and dial indicator readings were observed with 7 x 35 wide angle, short focus binoculars. The focal range of the binoculars was 6 to 12 feet.

The above described equipment provided satisfactory, reproducible data on all but the .016" and .010" wall, aluminum clad capsules. This latter cladding proved to be so weak that it deflected under slightest load application by the micrometers. As a result, the post-irradiation measurements obtained varied widely; and when it became apparent that these capsules had also been affected by internal gas pressure, additional effort in measuring these capsules was discontinued.

D. Hydraulic Pressurization Equipment

To accomplish the second objective of the program, i.e., to determine the extent the observed cladding strain will be repetitive in subsequent power generation cycles, equipment was built to permit cold hydraulic pressurization of the irradiated capsule cladding. In this manner, the capsule cladding could be shrunk back tightly over the pellets and the extent the pellets had receded from the cladding after irradiation determined.

The system designed for this purpose is shown schematically in Figure 14. The main components are the air-controlled hydraulic pump, a 1/2% accuracy pressure gage, an adjustable setting relief valve, and the autoclave vessel itself. The air-driven hydraulic pump is suitable for developing 5400 psi maximum water pressure with a 125 pound air supply. The outlet water pressure is continuously adjustable over the range using the pressure regulating valve on the air supply line. The autoclave vessel was designed for use on the same underwater tray used for dimensional measurements and employs a head closure suitable for removal and replacement using remote handling tools. Hydraulic pressure from the pump to the autoclave vessel is supplied through a 20 foot length of 1/4" high pressure stainless steel tubing. Operation of the system is straightforward and obvious from the construction description. About two minutes' hold time at maximum pressure was employed for the irradiated capsule pressurizations.

VIII. EXPERIMENTAL CAPSULE DESIGN

The basic capsule configuration employed in these irradiations was selected to simulate the APED reference fuel element design for a superheat reactor. It is annular geometry fuel element with a 1.25" O.D. outside cladding and 0.750" O.D. inside cladding. The active length of the fuel region is 4" and the over-all capsule length 5.85". The initial capsule design used for capsules numbered TR-1 through TR-22 is shown in Figure 15. In this design, the inert ZrO_2 pellets were 0.5" height, the end plugs 3/8" thick over-all and a total axial plenum of 0.1" was provided between the pellets and end plugs. Capsules TR-13 and 14 were exceptions in that the end plenum was reduced to zero to study this effect on axial clad expansion.

After the pellet gas evolution results became known, the capsule design was slightly modified to provide more internal free volume for gas expansion. In this design, Figure 16, the inert pellets were reduced to 0.250" height, the end plugs reduced to 5/16" thickness, and plenum support rings provided to prevent collapse of the cladding during hydraulic pressurization. This design was used for capsules TR-25 to TR-39.

The UO_2 enrichment in all capsules was 3.5% to provide a total capsule heat generation of 17 kw. This heat generation was selected to provide an average surface heat flux over the active fuel region of 350,000 BTU/hr-ft², equivalent to the maximum surface heat flux anticipated in superheat fuel element operation. The actual surface heat flux at a given total heat generation level, varies due to changes in the heat flow split between inner and outer cladding, as discussed in the Experimental Analysis section.

To accomplish objective 1 above, it was necessary to build capsules with a broad range of initial gaps and clad strengths. In order to extend the range of clad strengths down to that expected for stainless steel at superheat temperatures, while running the tests at essentially room temperature, a lower strength clad material than stainless steel was necessary. For this purpose, fully annealed 3003 Al cladding was chosen and approximately half the capsules in the program used this cladding. The remaining half used annealed 304 stainless steel cladding. The 0.2% offset yield point of the 3003 material is 6000 psi compared to approximately 12,000 psi short time tensile yield for 304 stainless at 1200 °F. Thus, for equal clad thicknesses, the Al can exert about one half the restraining force of stainless steel at 1200 °F on UO_2 growth. An additional advantage of the Al material is that the combined effect of its elastic modulus and yield point results in an elastic springback, in terms of strain, about equal to that for stainless at 1200 °F, following plastic strain.

The initial gap and clad thicknesses, along with the clad material employed, are listed in the first three columns of Table I for all of the capsules irradiated. The general intent in selecting the particular parameters incorporated in each capsule was to provide blocks of data that could be analyzed statistically to test the significance of each variable while minimizing the total number of individual capsules to be run. In this respect, the initial ten capsules, all aluminum clad, included four levels of each parameter, i.e., initial gap and clad strength. Similarly, the last fifteen capsules, TR-25 to TR-39, included five clad strength levels with three levels of initial gap spacing at each strength level.

The remainder of the capsules were selected to "spot check" the effect of other potential fabrication variables for superheat fuel. For example, all of the small gap spacing samples in the above groups were to be obtained by swaging the cladding. It was possible that these swaged capsules might act significantly different than unswaged capsules due to the pellet fracturing during swaging. Consequently, capsules TR-19 to 22 were built using hydraulic pressurization of the cladding to produce small gaps. The objectives in building the remaining capsules, not already discussed, were as follows:

1. TR-11 - to replace capsule TR-3 after it was run at excessive power.
2. TR-12 - to determine the gamma heating rate in the irradiation facility and assist the calibration of the heat generation instrumentation.
3. TR-13 and 14 - to determine the effect of zero axial gap on axial clad strain.
4. TR-15 to 18 - to provide data on clad strain at higher clad strengths than provided by the initial ten capsules.
5. TR-23 and 24 - to determine the clad strain produced by vibratory packed, arc-fused powder filled capsules.

IX. CAPSULE FABRICATION

A. UO₂ Pellets

The annular pellets used in the capsules were all fabricated from Spencer Chemical Company, ceramic grade UO₂ powder. The powder was ball milled with 3-5% wax to act as a die lubricant and binder and then pressed to a green density of 6 gms/cc. The green pellets were pre-sintered at 800 °F in a hydrogen atmosphere and then sintered at 2950 °F in hydrogen. All of the sintered pellets used in capsules were in excess of 95% of theoretical density as determined by the water displacement method.

Chemical, enrichment, and O/U analysis results for typical finished pellets are listed below:

Chemical:

Al - 20 ppm	31 - 30 ppm
Bi - <5 ppm	Ag - <0.5 ppm
B - <0.2 ppm	Na - <35 ppm
Cd - <2 ppm	Sn - 1 ppm
Ca - 5 ppm	V - <15 ppm
Cr - 70 ppm	Zn - 50 ppm
Co - <5 ppm	Sb - <2 ppm
Cu - 15 ppm	As - <5 ppm
Fe - 400 ppm	Mn - 10 ppm
Pb - 4 ppm	Mo - 3 ppm
Mg - 2 ppm	

Enrichment:

3.48%

O/U Ratio:

1.980	} 2 determinations
2.008	

As-sintered dimensions of the pellets were oversize on the O.D. and undersize on the I.D. The pellet O.D. was corrected to the desired value by wet, centerless grinding. The correct pellet I.D. was then precision ground concentric with O.D. Following grinding, the pellets were dried for several hours at 250 °F. The pellets were ground in individual lots of eight to obtain the desired initial gap for each capsule, based on dimensional measurements of the actual cladding to be used for the capsule. All of the pellets were 0.5 ± .010 in height, but the outside diameters varied by more than 75 mils to accommodate changes in the O.D. cladding thickness. Consequently, the total weight of fuel in the capsules varied by 25%. The tolerance obtained on the pellet O.D. was ± 0.5 mils and on the variation of the I.D. was ± 1.5 mils, with some taper. For the first twenty-two capsules built, the pellets were ground to provide identical cold diametral gaps between both the inside and outside clad. Since the experimental results had indicated no changes in the inside clad dimensions, the remaining capsules were fabricated with pellets sintered to be nominally oversize with respect to the inside clad. The only further I.D. grinding employed was to obtain assembly clearance for a few undersize pellets in the lot. However, measurements of the actual pellet O.D., I.D., and height were continued as usual.

B. Cladding

The stainless steel cladding used in the initial group of twenty-two capsules was machined from welded and drawn tubing ordered to ASTM Specification No. A-269-58 TP-304, annealed temper. The strength characteristics of actual samples of the cladding were not determined, but subsequent measurements on tubing from the same lots indicated 0.2% offset yield points ranging from 30,000 to 50,000 psi. The cladding was degreased, the outside diameter, inside diameter, and wall thickness measured at three points along the length, both at 0° and 90° orientations, and then packaged and labeled, along with end plugs machined from 304 bar stock, to insure use with the correct pellets during assembly. The capsule identification number was stamped into the recessed face of both end plugs. The stainless steel clad employed in the last group of fifteen capsules followed the same processing as above with the addition of a bright anneal at 1950 °F for 5 minutes, followed by rapid air cooling, before the cladding measurements were taken.

The aluminum cladding was machined from 3003 H-14 tubing and the aluminum end plugs from 1100 bar stock. All of the desired wall thicknesses could not be obtained in the aluminum tubing and had to be produced by chemically etching heavier wall stock. With the exception of the annealing treatment the aluminum cladding was processed in the same manner as the stainless steel clad above. All of the aluminum clad capsules were annealed after completion of the capsule assembly, by heating to 750 °F and holding at temperature for two hours, followed by furnace cooling.

C. Inert Pellets

The inert pellets used were pressed and sintered, CaO stabilized ZrO_2 . With only a few exceptions, the inert pellet dimensions were ground to the same dimensions as the fuel pellets in the same capsules. The exceptions were made on a few occasions where the use of inert pellets slightly undersize on the O.D. significantly expedited the capsule assembly.

D. Plenum Support Rings

The plenum support rings used in the last fifteen capsules were all machined from 304 stainless steel tubing to a slip fit clearance with the inside or outside clad.

E. Capsule Assembly

The assembly procedure for the initial twenty capsules in the program was as follows: One end plug was welded to the inside clad and the pellet column loaded onto the inside clad from the other end. The outside clad was then slipped down over the pellet column and welded to the end plug. The assembly and the remaining end plug were placed in a welding chamber, the chamber evacuated to approximately 10 microns pressure, and backfilled with helium. The remaining end plug was then inserted into the assembly and welded in place while maintaining the chamber inert atmosphere. All of the capsules welds were inert arc, fusion welds. The capsules were then removed from the weld chamber and mass spectrometer leak checked. An acceptable leak rate was less than 10^{-8} cc/sec. Some difficulty in passing the leak check was experienced with the very thin clad aluminum capsules due to weld porosity. These capsules were repaired, outside of the weld chamber, by making second pass over the weld area using an argon shielded arc.

Following leak check, the capsules were swaged, when called for, using a rotary swaging machine and steel dies. The die diameter was chosen to close the initial gap incorporated for assembly purposes and swaging continued, with the addition of shims, until either the desired capsule O.D. was obtained or until no further reduction in O.D. was possible. The aluminum capsules were then given the annealing heat treatment described earlier.

When the pellet gas release results became available, the assembly procedure was modified to include an outgassing step. This step was included in the assembly of capsules TR-18 and TR-22 through TR-39. Prior to the insertion of the last end plug, the capsule assemblies were placed in a vacuum retort and heated to 850 °F. At the same time, the retort was evacuated and pumping continued until a pressure of 10 microns was obtained. The usual pump-down time for pellet-filled capsules was about 2 hours but nearly 24 hours was required for the two powder filled capsules. The retort was then alternately backfilled with helium and evacuated a total of 6 times at temperature. After the final helium backfill, the retort was sealed, cooled to room temperature, and transferred to the weld chamber. The capsules were then unloaded under the chamber helium atmosphere, the end plug added and the final seal welds made. This outgassing step also provided the annealing heat treatment for the aluminum capsules in the group and no further annealing was performed.

EXPERIMENTAL RESULTS

A. Capsule Outside Diameter Growth

All of the irradiated capsules exhibited outside diameter growth, with the exception of two capsules - TR-30 and 35 - where the combination of clad strength, heat flux, and initial gap made growth unlikely based on over-all observed growth variation with these parameters. Figures 17, 18, and 19 are plots of the growth variation from point to point along the capsule length and are typical of all the results.

The definite upward slope of the diameter increase with axial location in some of these capsules is probably attributable to the axial neutron flux distribution at the irradiation position. The axial orientation of the capsules was controlled so that the higher numbered measurement points entered the neutron flux first, and thus, were always exposed to a higher than average flux. This observed slope is additional qualitative evidence for a functional relationship between the magnitude of the outside diameter growth and the capsule heat generation, as discussed in the subsequent section.

The "average" outside diameter growth was determined based on the individual growth measurements within the active fuel length of each capsule and is listed in column 8 of Table I for all the capsules irradiated. The "average" growth, thus determined, was also employed for the purpose of correlating the outside diameter results with heat flux, clad strength, and initial gap as discussed in the next section.

B. Capsule Inside Diameter Growth

Only one capsule exhibited a significant change in inside diameter and this diameter decrease was confined to the span of two measurement points on capsule TR-2 as shown in Figure 20. After this change was observed during the dimensional measurement data reduction, a duplicate set of measurements were made which confirmed the diameter decrease. Both sets of measurements were made within a week of the capsule irradiation. After about a month's decay, it became feasible to examine the inside diameter visually and no sign of the diameter decrease could be detected. A third set of measurements indicated that the diameter change had disappeared. There are two possible explanations for the above experience. The diameter decrease may have been simply the result of foreign material on the inside clad that was subsequently dislodged, or it could have been a slight inward buckle in the inside clad that was removed in subsequent handling. The capsules were manipulated under water with a bent aluminum rod that slipped into the central hole.

C. Capsule Length Changes

The initial capsule length measurements were taken between the cladding weld beads at either end of the capsules. The scattered data that resulted was at first attributed to the combined effect of inexact duplication of the capsule radial orientation for pre- and post-irradiation measurement and the undulations of the weld bead around the periphery of the capsule. The length measurement equipment was then modified to take readings between the recessed, plane faces of the capsule end plugs. Again, the same data scatter was obtained. Since the measurements were considered accurate, it appeared that the capsule length change was actually varying around the capsule circumference. However, it was inconceivable that the relatively heavy capsule end plugs could be bending as a result of forces from the relatively weak cladding. The only conceivable manner in which the end plugs could accommodate this length variation was by tilting with respect to each other.

In this event, the pattern of variation would be constrained to a sinusoidal path. When this criterion was applied to the length measurements, the sinusoidal pattern was readily evident. Figures 21, 22, and 23 are illustrative plots of this effect. These three plots were selected as the best demonstrations of the effect, but none of the curves for other capsules have more than one data point seriously out of line with a smooth curve.

It should be noted that the 0° or initial measurement point is arbitrary and not related to the capsule orientation with respect to the core during irradiation. This orientation is not controlled and probably accounts for the different phase angles between the plotted curves. The 0° measurement point is the same for both axial and radial measurements.

The variation in length growth around the capsule is probably the result of non-uniform heating due the radial neutron flux variation across the facility tube. The facility tube location is just beyond the peak of the GETR reflector spike where the flux begins to fall off rapidly. An attempt was made to reduce this effect in the last seventeen capsule irradiations by rotating the capsule 360° about its axis at the peak heat generation point. The procedure does not appear to have significantly reduced the variation as shown in Figure 24.

While most capsules were fabricated with approximately 0.1 axial clearance between the pellets and end plugs, capsules number TR-13, 14, 21 and 22 were deliberately built with zero axial clearance to test this effect. Comparison of the average axial growth in these capsules with similar capsules having axial clearance indicates little, if any, influence of the axial gap on the growth. If the axial growth was the result of UO_2 thermal expansion acting directly against the capsule end plugs, a profound effect should have been observed. Consequently, the axial capsule growth is believed to be the result of relatively localized action of the pellets, once the pellets have expanded radially into contact with the outside cladding.

On a qualitative basis, the amount of axial growth decreases with increased clad strength, but a quantitative relationship with this parameter and the effect of the other capsule parameters must be determined through a thorough analysis of all the axial growth results. This analysis has not yet been made and will be the subject of a subsequent report.

D. Circumferential Ridges

Visual post-irradiation examination of several of the capsules with low strength cladding revealed pronounced circumferential ridges over each pellet-to-pellet interface. The measured height of these ridges was 3-4 mils above the average cladding diameter in the most severe case encountered - capsule TR-3. A photograph of the ridges on capsule TR-3 is shown in Figure 25. The ridges were much more pronounced immediately after irradiation than indicated in the photograph, but have been partially obscured by cladding corrosion in the canal.

The severity of the ridges on capsule TR-3 is, in part, attributable to the extremely high heat generation incurred during irradiation as a result of an instrument failure. However, similar, less pronounced ridges were observed on TR-11, an identical replacement capsule for TR-3 irradiated at the desired heat generation rate. The common factor to all of the capsules exhibiting circumferential ridges appears to be the combination of weak cladding and a large initial gap. One explanation for the effect of the large gap on the appearance of ridges is believed to be its effect on the capsule heat transfer as discussed in detail in the data analysis section to follow. Essentially, the large gap shifts more of the capsule heat transfer to the outside surface approaching the limiting condition of a perfectly insulated inside surface. As a result, the inner pellet fibers grow more axially than the outer fibers and the short, annular pellets tend to assume an hourglass shape, projecting the upper and lower corners outward more than the center. These edges contact the outer clad first during expansion and form the observed ridges at the pellet interfaces. This explanation is consistent with the ORNL-GCRE experience using annular pellets without inside cooling. In their capsules, the appearance of ridges seems to be the rule rather than the exception.

E. Hydraulic Pressurization Results

The initial two capsules pressurized were TR-1 and TR-2 at 1000 psig. The results are shown in Figures 26 and 27 as a plot of post-irradiation and post-autoclaving dimensions relative to the initial dimensions of the capsule before irradiation. It is apparent that the O.D. of capsule TR-1 has returned to about its initial values or slightly less. The shrinkage on the O.D. of TR-2 was about half the growth experienced from irradiation. The visual appearance of both capsules was quite good with no evidence of wrinkling. As expected, the I.D. of both capsules increased. These two capsules were subsequently re-pressurized to 2000 psig with the indicated results. Both capsules are now about the same or somewhat smaller on the O.D. and somewhat larger on the I.D. than they were originally. Both capsules were then pressurized again to 4200 psig in order to determine what further shrinkage would take place.

The results of this pressurization were completely anomalous in that indicated capsule outside diameters were larger than those obtained after the 2000 psi pressurization and in one case larger than those obtained after 1000 psi pressurization (TR-1, 0° position). The capsule O.D. measurements were too accurate to account for most of this discrepancy and no explanation has been obtained for this result. The I.D. measurements were quite consistent and about as expected through the course of pressurizations.

Figs. 28, 29, 30 and 31 present the progressive changes in capsule dimensions due to irradiation and autoclaving for capsules TR-4 and TR-5. Again, the reduction of the post-irradiation clad diameter by hydraulic pressurization to about the initial clad dimensions is readily evident. The clad on capsule TR-4 did not quite come back to original pre-irradiation dimensions, probably due to the combination of the very small gap initially present and elastic "springback" of the cladding after pressurization. The cladding on capsule TR-5 was reduced to less than the pre-irradiation dimensions.

The above results can only be considered preliminary due to the few capsules pressurized and the possibility that the capsules tested were affected by internal gas pressure. Additional pressurizations will be performed on capsules without the internal gas pressure qualification. The conclusion drawn from the above results is that the UO_2 recedes to essentially its pre-irradiation dimensions following cooling after irradiation and that the circumferential cladding strain as a result of UO_2 expansion will be cyclic with power generation changes. The magnitude of the cyclic strain appears to be about equal to strain induced by the initial expansion cycle.

F. Capsule Growth Variation With Internal Heat Generation

Some of the evidence for the influence of internal heat generation on the capsule outside diameter growth has already been described under "Capsule Outside Diameter Growth". An actual correlation between the magnitude of the outside diameter growth and the capsule heat generation was obtained as a result of the repetitive irradiation of two capsules as shown in Figure 32. The abscissa of this plot is the average surface heat flux obtained by dividing the measured heat generation by the capsule surface area over the active fuel zone.

The ordinate is the "average" capsule growth over the active fuel zone defined previously. The slope of the two curves plotted are essentially identical and indicate 1.3 mils growth increase per 100,000 BTU/hr-ft² increase in the capsule average surface heat flux.

The original objective in undertaking the repetitive capsule irradiations was to determine whether the amount of growth would be progressive with the number of irradiation cycles. The correlation of growth with operating heat flux found for capsule TR-4 is so precise that it is difficult to attribute to chance alone. The four separate irradiations comprising the plot in Figure 32 were performed over a seven month period. The capsule was originally fabricated with the clad swaged down in contact with the UO_2 . Following both the second and third irradiation, the capsule was pressurized at 3000 psi to shrink the clad back to approximately its original dimensions. During the fourth irradiation the capsule was subjected to about five minutes of operation at the stated heat flux followed by nine more cycles of one minute's irradiation at full heat flux alternated with one minute's cooling completely withdrawn from the flux zone. When coupled with the results of the first two irradiations of capsule TR-5 discussed below, a definite correlation of growth with heat flux, or equivalently with a capsule heat generation, seems established.

Capsule TR-5 differed from TR-4 in that the clad thickness was .028" rather than .049" and the measured initial gap spacing was .007" rather than zero. The results are shown in Figure 32. It is immediately apparent that the slope of the growth variation with heat flux is essentially identical to that of TR-4, considering only the first two irradiations.

Following the second irradiation, the capsule was pressurized externally to 1500 psi and thereafter the growth does not correlate. The explanation for the deviation in TR-5 after autoclaving is believed to be the alteration of the inside gap by autoclaving and its effect on the capsule heat flow split. The inside gap of capsule TR-4 was quite small initially and would not be appreciably changed by autoclaving; about 1 mil average, based on actual measurements. On the other hand, the inside gap in TR-5 was initially significantly larger and was reduced approximately 7 mils by autoclaving. This change in the inside gap would effect a significant change in the distribution of heat to the inside and outside clads, as discussed in the data analysis section. More heat will flow to the inside clad, and for constant total capsule heat generation, commensurately reduce the outside surface heat flux. Since the outside diameter growth is probably directly related to the outside surface heat flux, the growth in TR-5 would be expected to be smaller after autoclaving as actually occurred.

The apparent linearity of the correlation curves of Figure 32 cannot be expected to persist to very low heat fluxes, particularly the curve for capsule TR-4. Linear extrapolation of the curve for TR-4 to zero heat flux would indicate almost 2 mils growth. Actually, both curves would be expected to bend in through the zero axis. The required steeply rising curve, at low heat fluxes for capsule TR-4, is believed to be another effect of relatively poor heat transfer between the pellets and cladding. Apparently, to transfer appreciable heat the pellet temperature must rise significantly relative to the clad and the pellets expand to develop significant interference pressure with the cladding even at low heat fluxes.

Two qualifications must be made with respect to the above correlation. The first is obvious in that the relation is based on the results from only two capsules, and as such, definitely requires further confirmation. The second qualification is the fact that, due to the capsules employed, the influence of internal gas pressure cannot be definitely ruled out. Further repetitive irradiations are planned using capsules known to be unaffected by internal gas pressure to place the correlation on firmer grounds.

G. Pellet Gas Evolution

As a result of the serious overheating and circumferential ridging observed on capsule TR-3, the capsule was transferred to the RML for more detailed examination. The best estimate of the average surface heat flux incurred during irradiation was 585,000 BTU/hr-ft². After photographing the capsule, it was punctured to obtain samples of the filler gas for analysis by gas chromatography. The results of the analysis are given in Table II.

TABLE II

GAS CHROMATOGRAPHY OF TR-3 FILLER GAS

<u>Sample #</u>	<u>He</u>	<u>% by Volume</u>					
		<u>H₂</u>	<u>O₂</u>	<u>N₂</u>	<u>CH₄</u>	<u>Xe</u>	<u>Kr</u>
#3	(18.5)*	23.0	12.8	9.6	36.1	---	---
#4	(19.5)*	22.9	13.3	9.6	34.7	---	---
#5	28.7	20.7	**	1.0	**	---	---

* Assumed by difference.

** Not analyzed.

--- Not detectible.

This gas analysis, in terms of observed components, is roughly comparable to that observed in the four superheat fuel elements previously irradiated in the GETR for 35 days at superheat temperatures. However, the residual percentage of the helium filler gas added initially is significantly lower.

The exact quantity of gas released cannot be determined because the original free volume of the capsule is unknown. However, an estimate of the volume was made based on the known fabrication parameters employed as follows:

$$\text{Outside clad-pellet gap} - \pi \times 1.150 \times .009 \times 5 = 0.1625 \text{ in}^3$$

$$\text{Inside clad-pellet gap} - \pi \times .750 \times .009 \times 5 = 0.106 \text{ in}^3$$

$$\text{End plenum} - \pi/4 [(1.150)^2 - (.750)^2] \times 0.1 = .0595 \text{ in}^3$$

$$\text{Open porosity in UO}_2 \text{ (0.2\%)} = .00476 \text{ in}^3$$

$$\text{TOTAL} - 0.33 \text{ in}^3$$

This is the volume of helium originally supplied to the capsule at one atmosphere pressure. Since the helium content was reduced to 20% of the total, four times the original volume of gas at one atmosphere pressure must have been released from the pellets or a total volume of 1.33 in³.

Subsequent to this result, several tests were made on the gas release due to heating on pellets selected from the APED production line. These pellets were fabricated by essentially the same procedure used for the Trail Cable capsule pellets. The pellets were all wet ground and then dried following sintering. Each sample included ten pellets.

TABLE III
GAS RELEASE FROM PRODUCTION LINE PELLETS

<u>Sample No.</u>	<u>T °C</u>	<u>Sample Weight</u>	<u>Gas Release cc/gm of Pellet</u>	<u>Calculated Release from TR-3</u>	
A	400°C	128 grams	7.61×10^{-2}	1.8 in ³	} Actual 1.33 in ³
B	600°C	137 grams	14.50×10^{-2}	3.4 in ³	
C	900°C	136 grams	10.56×10^{-2}	2.5 in ³	

In addition to the above gas volume, which included CO₂, A, O₂, H₂O, N₂, and H₂, some hydrocarbons were detected; but those were not identified or measured. Capsule TR-3 contained 386 grams of UO₂. Based on the above measurements, the expected release values from TR-3 are calculated in the last column above. The correspondence with the release observed in TR-3 (1.33 in³) is remarkably close.

Following the above results, the changes in capsule design and fabrication procedure were made to reduce the effect of pellet gas release. Capsule TR-30, incorporating these changes, was irradiated and then punctured for another filler gas analysis. The results are listed in Table IV below:

TABLE IV
GAS CHROMATOGRAPHY ANALYSIS OF TR-30 FILLER GAS (% by Volume)

<u>Sample</u>	<u>He</u>	<u>H₂</u>	<u>O₂</u>	<u>N₂</u>	<u>CH₄</u>	<u>CO</u>
#1	71	9	--	9	--	--
#3	72	11	--	10	--	4
#4	--	9	~0.2	11	1	4

The capsule internal void volume was experimentally determined to be 9.55 cc at 28 °C.

Based on the above analysis, the pellet gas release volume was calculated as 0.191 in³ compared to the 1.33 in³ in capsule TR-3. Since the fuel weights in the two capsules were nearly identical, the analyses indicated a factor of 6.8 reduction in the gas release attributable to the heating and evacuation step during fabrication. One qualification in the above conclusion is the fact that TR-3 was irradiated at significantly higher heat flux, and consequently, higher internal temperatures than TR-30. However, it appears that the internal temperatures in either capsule were sufficient to produce most of the gas release observed in the out-of-pile pellet gas release measurements; and, therefore, the above conclusion is reasonably valid.

A third post-irradiation filler gas analysis is planned for one of the powder filled capsules to evaluate the effectiveness of the fabrication heating and evacuation step on this material. The results will be presented in a subsequent report.

H. RML Examination of Capsule TR-3

Following the puncturing for filler gas analysis, capsule TR-3 was cut in half longitudinally, using an air motor driven abrasive wheel. A composite photograph of the sectioned capsule is shown in Figure 33.

The fuel is badly fractured, but it is impossible to tell how much of this fracturing was caused by the sectioning method. No gross deformation of the cladding was observed. However, a small crack was noticed in the end seal weld of the capsule.

A 1" sample was taken from the middle portion of a capsule half and mounted in Hysol for metallographic preparation of a radial fuel cross section. The sample was prepared for metallographic examination by a sequence of grinding, rough polishing, intermediate polishing, and final polishing. A number of voids were present in the UO_2 after the first sequence of preparation, so the entire procedure was repeated. The second preparation resulted in a UO_2 structure relatively free of voids. However, upon etching, the UO_2 stained sufficiently that nothing could be learned from the as-etched structure. A third sequence of preparation was undertaken and this time photographs were taken of the UO_2 structure in the as-polished condition as shown in Figs. 34, 35, and 36. Unusual fine scale porosity is present in the UO_2 . An odd void structure was also noticed near the center of the radial cross section.

All attempts to etch the UO_2 to reveal grain structure resulted in a surface too deeply stained to reveal an interpretable structure. It appeared as if there were a high concentration of some impurity which reacted readily in HNO_3 or H_2SO_4 . Etches using absolute C_2H_5OH with HNO_3 and/or H_2SO_4 also were tried with the same result. The pre-irradiation sample pellet analyses did not indicate any unusual constituent or concentration that would account for the staining and it is still unexplained.

I. Failure of Capsule TR-4

Capsule TR-4 was an .049" wall, aluminum clad capsule with the cladding initially swaged down over the UO_2 pellets. The capsule was subjected to thirteen cycles of full power operation in the course of the repetitive irradiations described earlier. Following the last irradiation cycle, the capsule was found to be leaking fission product gas into the facility tube. Examination of the capsule through the canal periscope revealed a fairly large pin hole in one of the weld beads. The visual appearance of the pin hole was essentially identical to the usual weld defects observed in aluminum. The aluminum surface around the hole was shiny and smoothly rounded into the bore of hole, similar in contour to a vortex. For the above reason, the hole is believed to have been

present in weld bead initially and probably lightly capped with aluminum when the weld was repaired. The hole was definitely not visually present before irradiation. Either due the strain on the weld due to clad growth during irradiation, or simply damage during handling, the cap over the hole was broken off and permitted the fission product release after the initial twelve cycles of irradiation.

J. Facility Gamma Heat Generation

In the course of calibrating the irradiation system instrumentation, considerable data were obtained on the facility tube gamma heat generation through the use of a lead filled dummy capsule TR-12. The peak gamma heat generation rate determined was 2.2 watts/gm at a position 9" above the bottom of the GETR core. Figure 37 is a plot of gamma heat generation variation with axial position.

XI. DATA ANALYSIS AND CORRELATION

A few introductory remarks are in order to provide perspective for the data analysis to follow. Not all of the capsule results can be considered of equal weight in the analysis. Instrumentation problems were encountered in the initial ten irradiations that introduced considerable uncertainty into the actual operating heat generation. This statement applies to capsules TR-1 through 7 and TR-15, 16 and 17. While the measured heat generation is stated in Table I for each of these capsules, these values are less certain than those stated for TR-8 to 14 and 18 to 36 inclusive. The growth results from the initial twenty capsules irradiated could have been influenced by internal pressure. On this basis, the results from capsules TR-7 through TR-10 were eliminated from consideration before any analysis work started, as discussed earlier. Preliminary data analysis revealed nearly twice the actual clad growth for capsules TR-1, 2 and 20 than that for any of the other capsules, including ones quite similar in fabrication parameters. These three capsules were also eliminated from further consideration. All of the remaining capsules were included, but a conscious effort was made to attach more significance to the results from the final seventeen capsules, where these problems had been eliminated. This effort is reflected in the choice of the best fit curve in some of the data plots and in the conclusions drawn.

Analysis of the results of these experiments was, unfortunately, not straightforward for at least three reasons: (a) The effect of three apparently independent variables was under investigation and the number of capsules available to test, quite limited. The initial intent had been to hold the capsule internal heat generation constant for most of the irradiations, thus, providing a two variable experiment; but this did not prove feasible. As a result, there are very few capsules with two of the variables close enough to provide a straightforward test of the third variable effect. (b) The individual increments in each variable were not discrete due to practical limitations in fabrication and operation. (c) Finally, it was not realistic to use the directly determined data of experiment without considerable analytically based corrections to account for known effects, particularly those effects indicated by the experiment itself.

All of the following data analysis and correlation work is concerned with the outside cladding growth using the "average" diameter change defined earlier as the basic experimental result. The outside clad growth is believed to be the result of UO_2 thermal expansion; and, consequently, the magnitude of the growth should be a function of the magnitude of the temperatures developed in the UO_2 during irradiation. In an annular capsule, the magnitude of the internal UO_2 temperatures depends not only on the total heat generation, which was experimentally determined but also on the heat flow split between the inside and outside clads. The heat flow split, in turn, depends primarily on the relative quality of the heat conduction paths between the UO_2 surface and the clad on the inside and outside.

A basis for correcting the growth results for variations in the total capsule heat generation was provided by the repetitive irradiation results where a correlation was obtained between the "average" clad growth and the capsule heat generation. Quantitatively, these experiments indicated a 1.3 mil increase in growth for each 100,000 BTU/hr-ft² increase in the capsule "average" surface heat flux, i.e., the slope of the curves in Figure 32. Using the capsule heat transfer model described

below, the above relationship may be converted to an effective thermal expansion coefficient for the UO_2 . Based on the peak temperature change, the effective coefficient is 1.8×10^{-6} in/in- $^{\circ}\text{F}$; based on the UO_2 volume average temperature change, the effective coefficient is 2.3×10^{-6} in/in- $^{\circ}\text{F}$. Both of the above values are about 30% of the literature value for the linear expansion coefficient of UO_2 . Using this slope, all the individual capsule growth data were corrected to common total heat generation equivalent to an "average" surface heat flux of 350,000 BTU/hr-ft² as indicated in column 2, Table V. Most of the capsules were irradiated reasonably close to 350,000 average heat flux so that the majority of the corrections were small.

To account for variation in heat split among the capsules, a semi-analytical approach was adopted. The basis for this approach is the assumption that the experimentally determined linear variation of clad growth with total heat generation is simply a reflection of growth dependence on a linear increase in the UO_2 volume average or peak temperature; whichever of the two parameters is the governing factor in the growth. Both of the parameters are linearly related to total heat generation in an individual capsule. A heat transfer model was set up that was considered the best representation of the heat transfer situation in the experiments. A constant average UO_2 thermal conductivity and a constant spatial distribution of heat generation within the UO_2 were assumed. The experimental results indicate that for essentially all of the capsules, the UO_2 expanded to close the outside gap and developed a large interference pressure between the UO_2 and the clad. To simulate the situation, a relatively high constant gap conductance was assumed to be applicable for all of the capsules. Based on relatively meager data on UO_2 contact coefficients with stainless steel and Zircaloy as a function of contact pressure in helium¹, the value of 5000 BTU/hr-ft² was taken as appropriate. In retrospect, this value is probably high, but the actual value selected has very little effect on the calculation results provided it is of the same order of magnitude. For a constant volumetric heat generation rate - equivalent to 350,000 BTU/hr-ft² average surface heat flux - the effect of different inside gap thicknesses at operating temperature on the UO_2 volume average and peak temperatures was calculated. The thermal conductivity of the gas in the inside gap was calculated on the basis of the gas mixture determined for capsule TR-30 by post-irradiation analysis. The resulting calculated curves are shown in Figures 38 and 39. The ordinates plotted are the ratio of the calculated volume average and peak UO_2 temperatures to the same quantities when inside and outside surface heat fluxes are equal.

The two curves are essentially identical and provide the same growth correction factor in all cases. Using these curves, all of the capsule growth results were corrected to the same volume average and peak temperatures as follows: The individual capsule inside gaps during operation were estimated. In the absence of better information, the UO_2 annulus thickness was assumed to remain constant during operation; and again, to reflect the experimental results, the operating inside gap was taken to be equal to the sum of the initial measured inside gap, the outside gap, and the observed growth corrected for springback as discussed below. Using the estimated "hot" inside gap and Figure 38 or 39, the ratios of the volume average and peak temperatures to those for the equal surface heat flux case were found for each capsule. The individual capsule growth results were then corrected to the same volume average and peak surface temperature using the above ratios and the UO_2 thermal expansion coefficient based on the observed growth variation with total heat generation. Presumably, the application of the above described corrections should have eliminated the influence of unequal heat generation and non-uniform heat split and placed all of the growth results on a common basis of volume average and peak UO_2 temperature.

TABLE V

APPLIED CORRECTIONS TO CAPSULE OUTSIDE DIAMETER FOR DATA CORRELATION PURPOSES

Capsule Number	Growth Correction To Uniform Heat Generation (350,000 "Average" Surface Heat Flux) (mils)	"Hot" Inside Diametral Gap (mils)	Ratio of Capsule Peak UO ₂ Temperature To Peak UO ₂ Temperature With Equal Surface Heat Flux Figure 38	Growth Correction To Uniform Peak UO ₂ Temperature (mils)	Observed Clad Permanent Strain (in/in)	Maximum Clad Stress (psi)	Maximum Clad Restraining Force-($\sigma t/r$) (psi)	Springback Correction (mils)	Gap Change in Heating To Clad Operating Temperature (mils)	Corrected Clad Growth (mils)	Estimated UO ₂ Growth (mils)
1	+2.5	18.4	1.14	-0.7	.00488	6,500	510	0.81	0.31	8.7	14.3
2	+0.5	18.5	1.14	-0.7	.00712	6,800	532	0.85	0.60	9.6	15.0
3	-3.1	26.5	1.22	-1.1	.00312	6,200	486	0.78	1.14	0.5	12.1
4	0.0	13.6	1.072	-0.3	.00480	6,500	510	0.81	0.68	6.5	8.8
5	0.0	19.6	1.16	-0.7	.00336	6,200	278	0.78	0.68	4.3	12.5
6	+1.7	16.7	1.12	-0.6	.00168	6,000	154	0.75	0.43	4.0	14.4
7											
8											
9											
10											
11	?	26.4	1.22	-1.1	.00200	6,000	472	0.75	0.68	2.2	14.0
12											
13	-1.0	4.6	0.90	+0.5	.00168	6,000	472	0.75	0.83	2.4	3.8
14											
15	?	8.4	0.98	+0.1	.00208	38,000	2,980	1.59	0.38	4.3	4.8
16	-0.6	9.4	1.00	+0.0	.00128	36,000	1,614	1.50	0.43	2.5	2.9
17	-0.6	8.7	.99	+1.0	.00368	40,700	1,042	1.70	0.43	6.7	7.1
18	-0.1	15.8	1.10	-0.5	.00240	38,800	744	1.61	0.39	4.0	5.2
19	+0.3	11.5	1.04	-0.2	.00256	39,000	1,750	1.62	0.35	4.9	9.6
20	+0.2	15.4	1.10	-0.5	.00848	43,200	?	1.80	0.36	12.1	14.4
21	+0.1	12.8	1.06	-0.3	.00224	38,500	1,728	1.60	0.37	4.2	9.9
22	-0.1	8.2	0.98	+0.1	.00296	39,800	1,020	1.66	0.39	5.4	5.9
23											
24											
25	-0.4	16.0	1.11	-0.5	.0044	6,400	502	.80	0.74	5.4	6.7
26	+0.6	16.0	1.11	-0.5	.00176	6,000	470	0.75	0.59	3.1	8.7
27	-0.2	24.4	1.21	-1.0	.00122	5,900	464	0.74	0.72	1.0	11.3
28	0.0	17.4	1.13	-0.6	.0044	6,400	286	0.80	0.68	5.7	7.6
29	0.0	18.3	1.14	-0.6	.00328	6,200	278	0.78	0.68	4.3	8.9
30	+0.6	8.8	0.99	+0.1	0	27,000 max.	2,120	1.12	0.33	1.8	6.2
31	-0.2	12.2	1.05	-0.2	.00160	37,000	1,660	1.54	0.40	3.1	5.1
32	-0.1	13.4	1.07	-0.3	.00144	36,500	934	1.53	0.39	2.9	3.8
33	+0.3	18.6	1.14	-0.7	.00016	5,000	224	0.63	0.64	0.4	10.0
34	+0.2	21.5	1.18	-0.9	.00064	33,000	2,586	1.37	0.36	1.5	7.5
35	+0.1	22.4	1.19	-0.9	0	27,000	2,120	1.12	0.37	0.3	11.8
36	-0.5	19.0	1.15	-0.7	.00296	39,800	1,786	1.66	0.42	4.2	8.6
37	-0.3	21.0	1.17	-0.8	.00016	29,000	1,300	1.21	0.41	0.3	10.9
38	-0.3	20.0	1.16	-0.8	.00328	40,200	1,030	1.68	0.40	4.7	7.2
39	+0.1	28.6	1.24	-1.1	.00176	37,300	956	1.55	0.37	2.8	12.8

Further corrections were applied to the observed growth results to account for elastic springback and to the initial outside gap values to account for the gap change in heating up to the capsule clad operating temperature. The conclusion of the capsule hydraulic pressurizations was that the UO_2 recedes to essentially its original dimensions upon cessation of irradiation. Consequently, the clad growth determined by post-irradiation measurements is the plastic clad strain induced but not the total extent of the strain occurring during irradiation, or the total extent of the UO_2 growth. The plastic strain differs from the total strain by the amount of elastic "springback" that occurs when the strain producing force is removed. The "springback" depends on the clad material elastic modulus and the maximum stress developed during the clad deformation. The springback corrections were determined using "typical" stress-strain curves for fully annealed 3003 Al and 304 stainless steel. The observed clad growth, in terms of strain, was plotted on the strain ordinate. An elastic modulus line was then extended from this strain intercept up to the intersection with the stress-strain curve. The projection of the elastic modulus line on the strain ordinate was taken as the elastic "springback". The cladding stress at the intersection of the elastic modulus line and the stress-strain curve was taken as the maximum stress during irradiation and used to calculate the retarding force on UO_2 growth, exerted by the clad using the relation $P = \frac{\sigma t}{r}$. This retarding force was taken as the basic measure of the clad strength and employed as the independent parameter in plots to determine the influence of clad strength on clad growth and UO_2 growth described later.

The small correction to the measured initial gap was calculated by determining the clad operating temperature based on the outside surface heat flux and then multiplying the difference between the clad operating temperature and room temperature by the difference between the thermal expansion coefficients of the clad material and UO_2 . Both the "springback" and gap corrections are listed in columns 9 and 10 respectively of Table V.

With all of the capsule growth data corrected to uniform volume average and peak UO_2 temperature, the influence of the initial gap and clad strength were determined by graphical plots versus these parameters. Two dependent parameters were investigated. The first parameter, identified as clad growth, is simply the measured clad growth, with corrections for UO_2 temperature variations and springback. The second, identified as estimated UO_2 growth, is the first parameter plus the corrected initial gap.

Figures 40 and 41 are plots of the two parameters vs. the initial gap incorporated in the capsule. The seemingly better correlation of Figure 41 is a result of including the independent parameter (initial gap) in the dependent parameter (estimated UO_2 growth). The conclusion derived from these two curves is that the clad growth decreases somewhat with increasing initial gap but not in direct proportion to the gap increase. The UO_2 apparently expands to close any size gap within the range studied and still produces permanent strain in the cladding. The clad growth for capsules TR-1 and 2 on Figure 40 are significantly above the results for all the rest of the capsules and, in particular, above that for capsule TR-26 which had similar fabrication parameters. The growth for capsule TR-20 does not even plot on the scale of the above figure whereas similar capsules TR-22 and 32 do. For this reason, these three capsules were assumed to be affected by internal gas pressure and were eliminated from subsequent data plots.

Figures 42 and 43 are plots of the corrected clad growth and estimated UO_2 growth vs. the calculated maximum clad restraining force developed during the irradiation. In Figure 43, the decrease in the estimated UO_2 growth with increasing clad strength is quite evident. Two curves are necessary to correlate the results, one for capsules with large initial gaps and a second for capsules with small initial gaps. Had sufficient intermediate gap capsules been irradiated, a third curve, intermediate between these two, would probably be required to correlate these results. The plot of clad growth vs. clad restraining force in Figure 42 does not provide a real correlation of the data without information gained from Figure 43. The downward trend with clad restraining force is obscured by the variation in the clad growth with initial gap and general scatter of the data. Nevertheless, Figure 42 is important, since it provides an indication of the maximum clad growth that will be experienced with a non-freestanding cladding, i.e., cladding with truly zero initial gap. Figure 43 could be subject to misinterpretation since it shows that the estimated UO_2 growth increases with larger initial gaps. However, as indicated in Figure 42, the amount of clad growth decreases with increasing initial gap. It is the amount of clad growth that will occur with zero initial gap that is of most interest and concern for non-freestanding clads, from the standpoint of plastic strain cycling.

Although the application of corrections to capsules TR-30 and 35 is carried through in Table V, these two capsules were not included in the data plots since no detectable clad growth was actually observed.

I. DISCUSSION OF RESULTS

A. Cladding Life To Failure From Plastic Strain Cycling

From the data of Figure 42, it is apparent that the maximum clad growth to be expected with the weakest cladding and zero initial gap will not exceed 10 mils, or equivalently, 0.8% total strain. An analysis has been made by G. F. Rieger of APED to predict the cladding life to failure from plastic strain cycling based on the above result. The general conclusion of his analysis is that thin superheat fuel element cladding will not fail due to this mechanism within the estimated total number of fuel element power cycles - approximately 500 - that will occur during the three year fuel element life. This conclusion was, of course, based on the presently available test data on the plastic strain cycle behavior of 304 stainless steel. The available 304 stainless steel test data is of very limited applicability to superheat conditions due to the absence in the tests of at least the following significant conditions involved in actual superheat environment:

1. Radiation.
2. Steam atmosphere.
3. Low frequency cycling with relaxation under loading.

Test programs are presently underway at APED as part of the AEC Superheat Development Program, to evaluate the effect of each of the above factors on the strain cycle behavior of 304 stainless steel and will provide a more realistic basis for evaluating the strain cycle life limitation. The above conclusion can only be tentative pending the outcome of these tests.

B. Influence of Internal Gas Pressure on Capsule Growth Results

The extent that the growth results from the initial twenty capsules were influenced by internal gas pressure due to fuel pellet gas evolution cannot be accurately determined. A calculation of the internal gas pressure depends on a knowledge of the actual free volume within the capsule and the effective "average" gas temperature during operation. Uncertainty in these quantities makes such a calculation only an order of magnitude estimate. The only real conclusion that can be drawn on the basis of calculations is that the internal gas pressure could have been a factor, particularly for the very thin aluminum clads and capsules with tightly swaged cladding.

When the results on pellet gas release became known, it was realized that annealing cycle employed with the aluminum capsules involved temperatures sufficient to produce almost all of the pellet gas release observed. Examination of the capsule dimensional data before and after annealing indicated that both the .016" and .010" wall, aluminum clad capsules had exhibited significant outside diameter growth during annealing. None of the other capsules showed any change in dimensions during the annealing cycle, but the relative severity of the annealing treatment vs. irradiation for producing the internal gas pressure effect on growth is unknown. The heat treatment may be actually more severe since the aluminum cladding is also heated to elevated temperature and suffers a severe loss in strength.

On the above basis, the irradiation induced growth results for capsules TR-7, 8, 9, and 10 were eliminated from further consideration and no additional capsules were built with this very low strength cladding. The growth results from the remainder of the initial twenty capsules were compared whenever possible, to subsequent results from capsules with similar fabrication parameters. The results from TR-1, 2 and 20 were eliminated on the basis of this comparison, but the rest are reasonably in line with later results. On the above basis, internal gas pressure is believed to have been, at most, a minor factor in the remaining capsules, of the initial twenty, that were employed in the data analysis and correlation work.

Calculations were made for the internal gas pressure in the final fifteen capsules, assuming only the free volume available in the end plenum and pellet gas release of the magnitude determined in TR-30. For an "effective" gas temperature of 2000°F, the internal gas pressure does not exceed 140 psi. Considering the minimum clad strength level employed in this group, the above internal pressure would not produce growth. Consequently, these latter capsules' results are believed to have been completely free of any internal gas pressure effect.

C. Effect of UO₂ Growth on Heat Transfer

The UO₂ thermal expansion indicated by these experiments should materially change the heat flow split between inside and outside surfaces of an annular element by the mechanism discussed in the data analysis section. To be realistic, the calculation procedures employed for the annular geometry elements should be revised to account for the unequal heat transfer resistance paths. For most situations, the shift in heat flow is favorable, i.e., the inside surface heat flux is reduced resulting in lower peak surface temperatures on the second pass of the conventional two-pass arrangement.

D. Effect of Pellet Gas Evolution on Heat Transfer

The gas evolution observed in the capsules of this experiment is probably typical of most fuel elements using conventionally processed, sintered UO₂ pellets. One effect of the gas release is to dilute the initial helium filler gas; and, thereby, reduce the thermal conductivity across internal gaps. Considerable experimental work has been performed in the past, particularly that to determine the effective thermal conductivity of UO₂, where analysis of the results involved assumptions concerning the gas conductivity in the pellet cladding gap. Re-examination of this work would appear to be in order based on the above results.

E. Further Plans For Experimental Work

No plans for the fabrication of additional capsules have been made. It appears that little additional insight can be gained concerning the plastic strain cycle mechanism from further capsules' irradiations in the Trail Cable Facility, as presently constituted. However, considerable experimental work remains, including some remaining new capsules not yet run and repeated irradiations of capsules already available to confirm some of the tentative or qualified conclusions of this report. This planned experimental work is summarized below in terms of the capsules to be run and the objectives accompanying each irradiation.

1. New Capsules

- a. TR-23 and 24. To determine the amount of cladding plastic strain with vibratory packed, arc-fused UO₂ powder filled capsules.
- b. D-1 through 6. These are 0.5 O.D., thin stainless steel clad, solid pellet filled capsules to determine whether the previously observed clad growth is peculiar to annular geometry capsules alone.

2. Previously Irradiated Capsules

- a. TR-32, 25, 24 and 38. Repeated irradiations at varying heat flux alternated with hydraulic pressurization to provide additional data on the capsule growth variation with internal heat generation and the extent the cladding growth will be cyclic with subsequent power generation cycles, particularly for capsules without qualifications due to internal gas pressure.
- b. TR-23. Post-irradiation filler gas analysis to determine the amount of gas evolution from powder fuel that has been deliberately outgassed during fabrication.

XIII. REFERENCES

1. Wheeler, R. G., Contact Resistance, HAP0, November 11, 1958.

XIV. ACKNOWLEDGEMENTS

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XV. APPENDIX

FIGURE 1

TRAIL CABLE FACILITY

NOTE: A. INSIDE OVERALL LENGTH 30 FT. 1 IN.
 B. TUBE EXTENDS 3 IN. BELOW BOTTOM OF CORE
 C. FOR CAPSULE 6" LG. MAX. O.D. = 2 1/4"

FIGURE 2
 INITIAL CAPSULE HOLDER DESIGN

FIGURE 3
CAPSULE HOLDER - ASSEMBLED AND DISASSEMBLED

FIGURE 4

REVISED CAPSULE HOLDER DESIGN

FIGURE 5

COOLING WATER SUPPLY SYSTEM SCHEMATIC

FIGURE 6

COOLING WATER SUPPLY SYSTEM EQUIPMENT

Figure 7
 RECORDER TRACE DURING IRRADIATION - CAPSULE TR-5

FIGURE 8

ORIGINAL DIMENSIONAL MEASUREMENT EQUIPMENT

NOTES

1. THERE IS $\pm 1/32$ VARIATION IN LOCATION OF MEASUREMENTS POINTS, AND FUEL ELEMENT END PLAY IS $1/32''$ TO $1/16''$ DEPENDING ON AMOUNT OF MELTING DURING END PLUG WELDING.
2. ACTUAL FUEL LENGTH IS $5.85'' \pm$ RATHER THAN $5-3/4''$. THUS, THE FUEL PELLETS HAVE $1/10''$ END PLAY.
3. NUMBERS CORRESPOND TO THOSE ON MEASUREMENTS JIG

FIGURE 9
CAPSULE MEASUREMENT POINTS

FIGURE 10

DIAL GUAGE MEASUREMENT EQUIPMENT

CAPSULE TR-32, DIMENSIONAL MEASUREMENT COMPARISON

TR-32 0° POSITION

FIGURE 11

CAPSULE TR-32, DIMENSIONAL MEASUREMENT COMPARISON
TR-32 90° POSITION

FIGURE 12

FIGURE 13

CAPSULE UNDERWATER MEASUREMENT

FIGURE 14

HYDRAULIC PRESSURIZATION SYSTEM SCHEMATIC

SCALE: FULL SIZE

FIGURE 15
INITIAL CAPSULE DESIGN

FIGURE 16
REVISED CAPSULE DESIGN

DIAMETRAL DIMENSIONAL CHANGES, TR-28, 3003 AL, .028" WALL;
ZERO GAP

FIGURE 17

FIGURE 18

DIAMETRAL DIMENSIONAL CHANGES, TR-31, .028" WALL;
CLAD SWAGED, 304 SS CLAD 3/29/61

DIAMETRAL DIMENSIONAL CHANGES, TR-38, 304 SS .016" WALL; .003" GAP

FIGURE 19

FIGURE 20
 DIMENSIONAL CHANGES
 TR-2
 .049" WALL; .003" GAP
 AVG. SURFACE HEAT FLUX = 309,000 BTU/Hr-FT²
 ALUMINUM CLAD

FIGURE 22

AXIAL DIMENSIONAL CHANGES, TR-22, 304 SS .016" WALL;
ZERO DIAMETRAL GAP, ZERO AXIAL GAP

AXIAL DIMENSIONAL CHANGE, TR-28,3003 AL, .028" WALL;
ZERO DIAMETRAL GAP

FIGURE 23

AXIAL DIMENSIONAL CHANGES, TR-39, 304 SS .016" WALL;
.009" DIAMETRAL GAP

FIGURE 24

CIRCUMFERENTIAL RIDGES ON CAPSULE TR-3
FIGURE 25

FIGURE 26
HYDRAULIC PRESSURIZATION RESULTS 0° POSITION - TR-1

FIGURE 27
HYDRAULIC PRESSURIZATION RESULTS 90° POSITION - TR-2

OBSERVED DIAMETER CHANGE VS. AXIAL POSITION, TR-4; 0° POSITION 5/31/61

FIGURE 28.

OBSERVED DIAMETER CHANGE VS. AXIAL POSITION, TR-4; 90° POSITION - 5/31/61

FIGURE 29

OBSERVED DIAMETER CHANGES VS. AXIAL POSITION, TR-5; 0° POSITION - 5/31/61

FIGURE 30

OBSERVED DIAMETER CHANGES VS. AXIAL POSITION, TR-5; 90° POSITION 5/31/61

FIGURE 31

FIGURE 32

FIGURE 33

LONGITUDINAL SECTION - CAPSULE TR-3

FORNIA PLANT OF FINE DIAMETER - 100 X (AS POLISHED)

FIGURE 34

METALLOGRAPHIC RESULTS

CAPSULE CROSS-SECTION - 4X

FUEL PELLET OUTSIDE DIAMETER - 100 X (AS POLISHED)

FIGURE 34

METALLOGRAPHIC RESULTS

VOID CLUSTER NEAR PELLET MID SECTION - 100X (AS POLISHED)

FUEL PELLET MIDSECTION - 100X (AS POLISHED)

FIGURE 35

METALLOGRAPHIC RESULTS

FUEL PELLET INSIDE DIAMETER - 100X (AS POLISHED)

FIGURE 36

METALLOGRAPHIC RESULTS

FIGURE 37
GAMMA HEATING RATE vs. INSERTION DEPTH

MAXIMUM PELLET TEMPERATURE RATIO VS. OPERATING INSIDE DIAMETRAL GAP
MODEL TRAIL CABLE SUPERHEAT CAPSULE, STAINLESS STEEL CLAD; 0.028" WALL

FIGURE 38

FIGURE 39

VOLUME AVERAGE TEMPERATURE RATIO VS. OPERATING INSIDE DIAMETRAL GAP
MODEL TRAIL CABLE SUPERHEAT CAPSULE, STAINLESS STEEL CLAD; 0.028" WALL

FIGURE 41