15

JUL 13 1965

12 #

MASTER

APPROVED FOR PUBLIC RELEASE

Westinghouse Atomic Power Division

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

FABRICATION AND IRRADIATION OF THIN-WALLED
TYPE 304 STAINLESS STEEL CLAD FUEL RODS
IN THE SAXTON REACTOR

D. R. McClintock
Materials and Processes Development

January 1965

Prepared for the U. S. Atomic Energy Commission
Under New York Operations Office Contract AT(30-1)-3269
(LRD-302)

WESTINGHOUSE ELECTRIC CORPORATION
Atomic Power Division
P. O. Box 355
Pittsburgh 30, Pennsylvania

49 page

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "Person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

EXTERNAL DISTRIBUTION

USAEC, New York Operations Office, 376 Hudson St., New York 14, N.Y. Director, Reactor Development Division	3
USAEC, Resident Engineer, Westinghouse Atomic Power Division	1
USAEC, Division of Reactor Development and Technology, Washington 25, D. C. Attn: W. R. Voigt	3
USAEC, Division of Technical Information, P. O. Box 62, Oak Ridge, Tennessee	15
USAEC, Assistant General Counsel for Patents, Germantown, Maryland Attn: R. A. Anderson	1
General Electric Atomic Power Equipment Dept., 2151 South First St., San Jose, California, Attn: Aileen Thompson	2
The Babcock & Wilcox Co., Atomic Energy Division, 1201 Kemper St., P. O. Box 1260, Lynchburg, Virginia, Attn: J. W. Landis	2
Allis-Chalmers Manufacturing Co., Nuclear Power Dept. - Greendale, P. O. Box 512, Milwaukee 1, Wisconsin, Attn: C. B. Graham	2
Combustion Engineering, Inc., Nuclear Division, Windsor, Connecticut, Attn: A. F. Miller	2
Hanford Atomic Products Operations, General Electric Co., Richland, Washington, Attn: W. S. Dowis	2
Argonne National Laboratory, P. O. Box 299, Lemont, Illinois, Attn: A. V. Crewe	2
Yankee Atomic Electric Co., 441 Stuart St., Boston 16, Massachusetts, Attn: R. J. Coe	1
Yankee Atomic Electric Co., 441 Stuart St., Boston 16, Massachusetts, Attn: D. E. Vandenburg	1
Los Angeles Dept. of Water & Power, 207 South Broadway, P. O. Box 3669, Terminal Annex, Los Angeles 54, California, Attn: S. B. Nelson	1
Connecticut Yankee Atomic Power Co., P. O. Box 2010, Hartford 1, Connecticut, Attn: S. R. Knapp	1
Southern California Edison Co., P. O. Box 351, Los Angeles 53, California, Attn: J. F. Davenport	1
Southern California Edison Co., P. O. Box 351, Los Angeles 53, California, Attn: J. B. Henderson	1
San Diego Gas & Electric Co., P. O. Box 1831, San Diego 12, California Attn: C. M. Laffoon	1

TOTAL 42

TABLE OF CONTENTS

	<u>Page</u>
Table of Contents -----	ii
List of Figures -----	iii
List of Tables -----	iv
Abstract -----	v
1. Introduction -----	1
2. Design and Fabrication of the Experiment -----	2
A. Thin-Walled Cladding -----	2
B. Fuel Rod Specimen -----	3
C. Modified Saxton Removable 3 x 3 Assembly -----	5
3. Reactor Operating Conditions -----	7
4. Post Irradiation Examinations -----	8
A. Visual and Dimensional Examination -----	8
B. Gamma Activity Profile Determination -----	9
C. Burnup Determination from Cs-137 Analysis -----	9
D. Cladding Examination -----	10
5. Discussion of Cladding Performance -----	12
6. Conclusions -----	14
7. Acknowledgements -----	15
8. References -----	16

APPENDICES

A. Chemical Analysis of Thin-Walled Cladding -----	40
B. Mechanical Properties of Thin-Walled Cladding -----	41
C. Fuel Rod Fabrication Schematic -----	42
D. Metallographic Specimen Preparation -----	43

LIST OF FIGURES

	<u>PAGE</u>
1. Photomicrographs of Lot "A" Thin-Walled Stainless Steel Clad -----	20
2. Photomicrographs of Lot "B" Thin-Walled Stainless Steel Clad -----	21
3. Design of Fuel Rod Specimen -----	22
4. End Closure Design Used With Thin-Walled Clad -----	23
5. Typical Weldment of the Thin-Walled Cladding -----	23
6. Typical Fillet Configurations of Welds -----	24
7. Modified Removable 3 x 3 Sub-Assembly -----	25
8. Disassembled Fuel Bearing Portion of Saxton Modified 3 x 3 Fuel Assembly -----	26
9. Plan View of Saxton Core Illustrating Location of Modified 3 x 3 Sub-Assemblies -----	27
10. Saxton Operating History -----	28
11. Saxton Main Coolant Chemistry -----	29
12. Modified 3 x 3 Sub-Assembly #21 Following Removal From the Saxton Core -----	30
13. Visual Examination Summary - Rod #13 -----	31
14. Visual Examination Summary - Rod #14 -----	32
15. Visual Examination Summary - Rod #22 -----	33
16. Crud Deposition on Rod #13 -----	34
17. Plastic Deformation of Clad Into Unsupported Plenum -----	35
18. Gamma Scan - Fuel Rod #14 -----	36
19. Fretted Area of Thin-Walled Cladding -----	37
20. Longitudinal Ridge on Thin-Walled Cladding -----	38
21. Buckling of Thin-Walled Cladding -----	39

LIST OF TABLES

	<u>PAGE</u>
Table I	Summary of Fuel Rod Fabrication Data ----- 17
Table II	Data Summary of Thin-Walled Stainless Steel Clad Rods ----- 18
Table III	Maximum Clad Stresses and Estimated Yield Strength for Beginning and End of Life Over Pressure Conditions ----- 19

ABSTRACT

Ten thin-walled (9.7 mils) Type 304 stainless steel clad fuel rods were irradiated as part of the Saxton core to a maximum burnup of 8900 MWD/MTU at a maximum heat flux of 410,000 Btu/hr/ft². The corresponding integrated fast flux exposure (> 1 Mev) was 1.1×10^{21} nvt. Post-irradiation examinations revealed no evidence of failure or crack formation although the thin-walled clad was subjected to plastic deformation. The successful operation of this engineering proof test emphasizes the satisfactory performance of stainless steel in a borated pressurized water environment.

1. INTRODUCTION

It is very desirable to reduce nuclear fuel cycle costs for power reactors. A major factor in achieving this aim is to improve neutron economy. In the case of stainless steel clad fuel rods, the most logical approach to neutron economy is reduction of the cladding wall thickness. This results in a departure from the free-standing design concept to the case where the clad tube requires support from the fuel in order to prevent collapse at operating conditions.

An engineering proof test was performed in the Saxton reactor to investigate the in-pile performance of fuel rods clad with thin-walled (9.7 mils) slightly cold worked type 304 stainless steel. The experimental utilized ten fuel rods designed to operate at 13.5 kw/ft peak power density and 10,000 MWD/MTU maximum burnup. The rods were incorporated into two modified Saxton removable 3 x 3 subassemblies. These were installed into the Saxton core in February 1963 and were irradiated until November 1963. The rods in the lead assembly, which had operated in a central core location, experienced a peak burnup of 8900 MWD/MTU with a corresponding fast flux exposure (> 1 Mev) of 1.1×10^{21} nvt. Post-irradiation examinations were performed in the canal at the Saxton reactor and at the Westinghouse Post-Irradiation Facility Hot Cells at Waltz Mill, Pennsylvania.

2. DESIGN AND FABRICATION OF THE EXPERIMENT

A. Thin-Walled Cladding

The 304 stainless steel tubing used for the fabrication of the thin-walled fuel rods was purchased and inspected pursuant with the same material standards ⁽¹⁾ used for the procurement of the standard 15 mil wall cladding of the Saxton Reactor core. The material was received from the vendor in two lots, A and B. Upon receipt of the incoming tubing a 100% eddy current inspection was performed. The acceptable pieces were then further tested ultrasonically. Only those pieces acceptable by both tests were selected. The acceptable tubing was then dimensionally inspected for wall thickness, ovality, and camber. The wall-thickness tolerance on the 9.5 mil wall tubing was held to $\pm 1/2$ mil. All rods fell within this range, the average wall thickness being 9.7 mils.

Samples of the incoming tubing were also obtained for chemical analysis and mechanical tests. The results are detailed in Appendix A and B respectively. Visual examination of the two lots of tubing revealed a variant in the physical appearance. The "A" lot of tubing had a bright finish and the "B" lot a dull finish. Metallographic examination and grain size determination of each lot of tubing was performed and representative photomicrographs are illustrated by Figures 1 and 2. Very little difference in the metallographic appearance of the two lots of material was observed.

The design of the thin-walled stainless steel clad required a balance between the elastic instability pressure, the clad thickness, the clad stresses, and the pellet-to-clad gap. As the clad thickness decreases, clad stresses rise. The clad stresses are a function of the pellet-to-clad gap, rising with increasing gap. The initial elastic instability pressure is strongly dependent upon the clad thickness.

The stresses and strains in the clad under various operating conditions were calculated.^(1,2) As the reactor pressure and temperature are increased the clad will become elastically unstable when the coolant pressure reaches approximately 700 psi. At the zero power condition, 2000 psi coolant pressure and 430°F, the maximum clad stress is approximately 80,500 psi compression. This stress was determined using elastic methods and is a combination of direct stress and bending stress in the circumferential direction. The yield stress of the clad at this temperature was approximately 72,000 psi. Thus, it was expected that there would be some localized plastic yielding. A maximum localized permanent strain of approximately 0.4% was calculated at the zero power condition. During operation, as the reactor is brought to power the pellets expand faster than the clad and therefore push the clad back towards a circular shape. In the extreme case (maximum temperature, worst tolerance condition), the clad will be stretched to a maximum tensile stress of 27,700 psi. The yield stress of the material at the mean operating clad temperature of 672°F is approximately 64,000 psi, so that no yielding of the clad occurs.

B. Fuel Rod Specimen

The design of the thin-walled fuel rods is illustrated in Figure 3. Fabrication parameters, including cladding diameter and wall thickness, fuel pellet diameter and enrichments, cold diametrical gaps between pellet and clad, unsupported plenum weights, and total fuel weights are summarized in Table I. Each rod contained a space, or plenum, between the top end plugs and the UO_2 fuel column to accommodate released fission product gas. The clad surrounding the space was supported by a stainless steel sleeve, except for a gap of approximately 0.3 inches between the sleeve and the end plug to allow for axial expansion of the fuel column. All end plugs were machined from 304 stainless steel bar stock.

The fuel used to fabricate the rods was in the form of cylindrical pellets of enriched UO_2 having a density of 10.4 g/cc (95% of theoretical). A spherical depression, or dish, was provided at each end of the individual pellets (0.300 inches diameter and 14 mils deep). This dish provided for the differential thermal expansion across the fuel and thus reduced overall fuel column growth during operation.⁽³⁾ The enrichment of the UO_2 fuel pellets is given in Table I.

The UO_2 fuel pellets were loaded into pre-cut lengths of the thin-walled tubing which had the bottom end plug previously welded in place. The assembly and end closure welding of the rods were performed in air. Following end closure welding each element was radiographed and leak tested in helium. A flow schematic of the fabrication sequence is given in Appendix C.

Previous end closure designs used successfully with the TIG welding process would not produce acceptable welds with the thin-walled stainless steel tubing. The butt type weld joint design was determined to be unacceptable when used in conjunction with tubing that has a wall thickness of less than 10 mils. During the welding operation the thin section heats and melts rapidly while the heavier section heats and melts relatively slowly: then, due to the unbalanced cooling, the weld contracts toward the end plug during freezing thus causing a void formation on the tube side of the weld. This is identified as a shrinkage defect.

To permit utilization of the TIG welding equipment available at this laboratory an end plug was designed that could be welded to the thin-walled tubing. The design, illustrated in Figure 4, entailed the use of a plug with a heavy section that would take most of the heat away from the tubing while assuring adequate penetration without peel back or burn through.

As depicted by Figure 4, the weld was accomplished by bringing the electrode in contact with the raised lip on the end plug at an angle of 45°. This prevented the electrodes from coming in contact with the thin-walled tubing and directs the penetration into the end plug, thus dissipating the majority of the energy to the end plug. The melted metal of the lip flows into contact with the tubing and a satisfactory weld joint, as illustrated in Figures 5 and 6, are achieved upon cooling.

C. Modified Saxton Removable 3 x 3 Assemblies

The Saxton core is unique in that provision has been made for five removable subassemblies of nine rods each. Special ports in the reactor vessel head permit insertion and withdrawal of these subassemblies without the necessity of removing the reactor head. In addition, water flow and temperature can be determined at the outlet of these subassemblies through the use of a combination thermocouple-pitot tube unit.

To utilize more fully the flexibility provided by Saxton, the design of the standard removable 3 x 3 assembly was modified to permit removal and insertion of individual fuel rods. Thus, fuel rods are available for examination or replacement without reactor head removal or destruction of the containing assembly. As illustrated in Figure 7, the assembly is separable into two major parts: the fuel-bearing portion, which was designed to coincide with the reactor core; and a removable supporting structure. The fuel assembly section consisted of a perforated enclosure with spring clip-type grids to hold and position the fuel rods. This allowed the fuel rods to expand freely with changes in operating power. The top end-plate was fabricated with extended posts and holes through which the removable fuel rod end plugs protruded. Upon removal of the support section, the protruding fuel rod end plugs were exposed so they could be extracted

with a special tool.⁽⁴⁾ Two modified removable 3 x 3 sub-assemblies (identified as No. 21 and No. 22) were inserted into the Saxton core. Each of the assemblies contained five thin-walled stainless steel clad fuel rods and four free-standing Zircaloy clad fuel rods as shown in Figure 8. Four of the stainless steel clad rods in each assembly were removable. The location and orientation of the assemblies while operating as a part of the Saxton core is illustrated in Figure 9.

3. REACTOR OPERATING CONDITIONS

The two modified removable 3 x 3 assemblies, which contain the ten thin-walled stainless steel clad fuel rods, were operated as part of the Saxton core for a total of 93,000 MWH (4650 EFPH at 20 MW). The reactor operating history for this period is shown graphically in Figure 11. During this time the reactor experienced 48 hot shutdowns or scrams, where coolant temperature and pressure were maintained, and four cold shutdowns.

Reactor coolant chemistry for the period of interest is illustrated in Figure 10. Throughout most of this time, the reactor operated with 2 to 4 ppm of potassium in the coolant except during short periods when the potassium was intentionally removed to study the effects of coolant pH changes on the core reactivity. From about the middle of May until the end of the experiment, the coolant boron concentration was decreased steadily from 1200 to approximately 750 ppm to compensate for the core burnup. Prior to May 1963, boron was used only during reactor shutdown.

4. POST-IRRADIATION EXAMINATIONS

A. Visual and Dimensional Examination

At the conclusion of the reactor operating cycle in November 1963, the modified 3 x 3 assemblies were removed from the Saxton core. Assembly No. 22, which had operated in a peripheral reactor location, was visually examined at the site. The lead assembly, No. 21, representing the maximum exposure, was transferred to the Westinghouse hot cells for extensive visual and destructive examinations. The appearance of the assembly prior to removal of the fuel rods is illustrated in Figure 12 and an examination summary for three of the removable rods is given in Figures 13-15. The results of the visual examinations can be summarized as follows:

- (1) No evidence of failure or clad rupture was observed.
- (2) Plastic deformation in the unsupported plenum area and longitudinal ridging were exhibited by certain of the thin-walled stainless steel clad fuel rods, as detailed in Table II.
- (3) Fretting, which does not occur on the standard Saxton rods, was exhibited by the thin-walled rods.
- (4) The crud deposition was, in general, very light. Most of the visible deposition was observed in the high heat flux region of assembly No. 21. The fuel rods comprising the peripheral assembly (No. 22), which operated at the lower heat flux level, exhibited no significant crud deposition.

Figure 16 illustrates the appearance of the corrosion product at the region of maximum heat flux on fuel rod No. 13, as viewed through a remotely operated Bausch and Lomb stereomicroscope at 3.3X. The maximum crud thickness was determined to be approximately 1.5 mils at this location. The average crud surface deposition was approximately 70 mg/dm^2 in the area where crud deposition occurred. However, overall crud deposition averaged only about 8.2 mg/dm^2 since much of the rod surfaces were clean.

Plastic deformation of the clad in the unsupported section of the fission gas plenum is illustrated in Figure 17. As detailed in Table II, longitudinal ridges were observed on some of the rods. No evidence of failure or rupture was observed.

Dimensional measurements were performed on three fuel rods taken from the assembly which had experienced the maximum exposure. Remote measurements were taken at 0° and 90° at six inch intervals along the rod length with a standard vernier micrometer. The results, verified the presence of a longitudinal ridge on each of the three rods. The maximum ridge heights are included in Table II. Length measurements were made and recorded to the nearest mil. No changes in rod length were detected.

B. Gamma Activity Profile Determination

A gamma activity profile was obtained to determine thermal neutron flux profile during irradiation. The method used for gamma scanning at the Westinghouse hot cells consisted of vertically transversing the fuel rod across a slit in a lead collimating block. The gamma radiation thus admitted was directed to a shielded NaI (Tl activated) scintillation crystal. The scintillation crystal and a digital recorder are located out of the cell. Since the equipment would not permit a continuous gamma scan, gamma activity measurements were obtained at intervals over the length of the fuel rod. These values were then plotted, Figure 18, and the curve was used to select burnup and metallographic samples from the region of maximum exposure.

C. Burnup Determinations

The burnup experienced by the rods representing maximum exposure was determined by analyses of the cesium-137 fission product nuclei. Three samples from the region of maximum exposure were obtained from fuel

rod No. 14. The neutron flux of an enriched UO_2 fuel pellet is not uniform throughout the diameter because of the greater neutron absorption in the surface layer. For this reason, the entire UO_2 fuel pellet, including the surrounding stainless steel cladding, was immersed in hot concentrated nitric acid to reduce error due to the migration of cesium in the fuel.^(6,7) Thus, the cesium 137 within the UO_2 fuel as well as any cesium which may have been deposited on the inside surface of the cladding, would also have gone into solution. The calculation methods used to compute burnup values from the cesium-137 fission product nuclide analyses are the same as those employed in Appendix E. of Reference 4. The results are reported in Table II.

D. Cladding Examination

A careful microscopic examination was performed on certain select samples of the cladding from fuel Nos. 13 and 14 prepared by the technique described by Appendix D. No evidence of failure, cracking, or stress corrosion attack was observed. Micro-hardness values were obtained on samples representing the region of maximum fast flux exposure and plastic deformation. The results indicate a general increase in hardness from a pre-irradiated value of 250 KHN (about 84,000 psi yield) to approximately 320 KHN (about 120,000 psi yield) in the high exposure region. Knoop hardness values in excess of 400 were recorded at the location of severe plastic deformation, indicating a yield strength of approximately 150,000 psi.

Chemical and radiochemical analyses were performed on three samples of the cladding. These samples were obtained from the region of maximum exposure of fuel rod No. 14 to permit dosimetry determination of the neutron flux. The samples were dissolved in concentrated hydrochloric acid and the solutions were diluted volumetrically for analyses. The dosimetry calculations were based on the conversion of Fe-54 to

Mn-54 an (n,p) reaction. Burnup due to thermal neutron absorption is insignificant and the data obtained by this method are less sensitive to error caused by high thermal flux and long term exposure.⁽⁷⁾ The maximum integrated fast flux exposure values are reported in Table II.

The thin-walled cladding did not exhibit any change in the basic microstructure as a result of irradiation, and no evidence of a reaction zone between the UO_2 fuel and the stainless steel was observed on the clad inner surface. Figure 19 is a transverse section of the cladding at the point where the supporting fingers of the grid made contact and illustrates a typical fretted area. The fretting is attributed to inadequate support since the grid fingers had been designed to accommodate a standard Saxton rod having a larger diameter. This loose fit caused the fretting, which does not occur on the standard Saxton rods. No increase in hardness nor alteration of grain structure of the metal below the fretted surface were observed. As shown in Figures 20 and 21, metallographic examination of the longitudinal ridges and the unsupported section of the fission gas plenum where plastic deformation occurred did not exhibit any evidence of crack formation.

5. DISCUSSION OF THE CLAD PERFORMANCE

The thin-walled stainless steel clad fulfilled its primary purpose of providing containment for the fuel and its fission products. No failures occurred and metallographic examination indicated no evidence of crack formation. The presence of axial ridges and plastic deformation in the plenum region on some of the fuel rods raises questions as to what caused them, when they occurred, and whether they were detrimental to successful fuel rod operation.

Under normal zero power conditions, the maximum circumferential stress in the clad exceeds the yield strength of the material and a small amount of plastic deformation can be expected. The thin-walled fuel rods were fabricated from two lots of material having different yield strengths as detailed in Appendix B. As part of the plant hydro test prior to operation, the fuel rods were subjected to an over-pressure (i.e., higher than the nominal 2000 psia operating pressure) of 2395 psi at 522°F. Following operation, the rods were again subjected to an over-pressure condition of 2560 psi at 515°F. Considering that irradiation hardening of the material increased the yield strength approximately 50% and that a minimum of 300 psi internal pressure was generated due to fission gas release, the beginning of life hydro test resulted in a more severe condition than the over-pressure condition at the end of life. Therefore, it is concluded that the axial ridges were formed probably prior to power operation of the rods. The calculated stresses during the pre- and post-operation over-pressure conditions, including estimated yield strength for the two lots of material, are given in Table III.

Longitudinal ridges were visually observed on four of the rods. Diameter measurements, performed on three rods from the assembly which had experienced the maximum exposure, indicated the presence of a five-mil ridge on rod No. 13, which was not visually apparent. Thus, it is probable that all of the rods have ridges. The results of the diameter measurements on the three rods indicate that the maximum ridge height was 20 mils. Figure 20 illustrates a section through the 20-mil ridge on rod No. 14. No wrinkles were observed as would be expected with large clad-to-pellet clearances.

After the initial installation and zero power exposure, the clad stresses operate wholly in the elastic range. The over-pressure exposure prior to operation produced stresses and plastic deformation greater than those experienced during zero power exposure. However, subsequent operation at full power would tend to push the clad back towards a circular shape and may have served to reduce the ridge height. It is probable that clad stresses during in-pile cycling were within the elastic range and it is concluded that the presence of the minor ridges in the clad was not basically detrimental to successful fuel rod operation.

The extent of the plastic deformation of the unsupported clad into the plenum at the end of the rod is shown in Figures 17 and 21. As in the case of the longitudinal ridges, the plastic deformation probably occurred during the exposure to 2395 psi coolant pressure at 522°F before operation, since the clad stresses were higher at this time than during either the full power operating condition or the end of life 2560 psi over-pressure condition at 515°F. The irradiation hardening of the material makes plastic deformation at the end of life even more unlikely. Some of the fuel rods plastically deformed into the gap between the sleeve and end plugs while others did not. This reflects the difference in the mechanical properties of the two lots of material used to fabricate the rods (see Appendix B). All of the rods clad with material from lot "B" deformed, plastically, as compared to only 3 of 7 rods fabricated from lot "A" material. Among the rods from lot "A" there appears to be a correlation between the length of the unsupported gap and the occurrence of plastic deformation. With the exception of rod No. 6, no plastic deformation was observed on rods having gap lengths less than 0.316-inch.

The purpose of the unsupported gap was to provide space to accommodate the differential axial expansion between the fuel column and the clad. The conclusion that the plastic deformation occurred prior to irradiation is considered significant since the rods operated satisfactorily without axial expansion space. The lengths of rods 13 and 14 were measured following exposure and the results are listed in Table II. They remained within the drawing tolerance, indicating that no discernible length increase occurred. Thus, the presence of the plastically deformed area was not detrimental to the successful operation of the fuel rod clad.

6. CONCLUSIONS

The thin-walled stainless steel clad fuel rods operated satisfactorily to the completion of the test. A peak burnup of 9450 MWD/MTU at a maximum heat flux of 440,000 Btu/hr ft² was experienced, and the cold-worked stainless steel clad, although subjected to severe local plastic deformation prior to operation, did not rupture or exhibit any evidence of crack formation. The fretting, the longitudinal ridges, and the plastic deformation had no adverse effects on the in-pile performance of the thin-walled rods. Thus successful operation of this engineering proof test re-emphasizes the satisfactory performance of stainless steel in a borated pressurized water environment.

7. ACKNOWLEDGEMENTS

The author would like to acknowledge the valuable assistance of Dr. H. M. Ferrari and Mr. E. Paxson for their helpful comments and suggestions during the preparation of this manuscript. Acknowledgements are also made to Mr. Paxson for his effort toward the design of the thin-walled fuel rods and to Mr. Galm and the Westinghouse Post Irradiation Facility personnel at Waltz Mill for their assistance in the post irradiation examinations. The author is indebted to Messrs. J. Hagood, and M. E. Rinker for their assistance in the fabrication of the test assembly and to Mr. A. F. Mattis for the compilation and reduction of data.

8. REFERENCES

1. Large Reactor Development Quarterly Progress Report, September-November 1961 WCAP-3707.
2. Large Reactor Development Quarterly Progress Report, March-June, 1962, WCAP-3710.
3. "Fabrication and Irradiation of Stainless Steel Clad UO_2 Fuel Rods," (The LRD In-Pile Chemical Shim Loop Experiment), by D. R. McClintock, and C. J. Kubit, April 1964, WCAP-3734.
4. Large Reactor Development Quarterly Progress Report, April-June 1963, WCAP-3739.
5. T. J. Slosek and B. Weidenbaum, "Irradiation and Examination of Vibratory Packed UO_2 High Burnup Program Elements," GEAP-3108, Part 2 (February 1960).
6. J. L. Bates, J. A. Christensen, and W. E. Raoke, "Fission Products and Plutonium Migrate in Uranium-Dioxide Fuel," Nucleonics 20, No. 3, March 1962.
7. W. E. Murr, et. al., "Effects of Large Neutron Doses and Elevated Temperature on Type 347 Stainless," BMI-1609, January 1963.

TABLE I

SUMMARY OF FUEL ROD FABRICATION DATA

Ass'y No.	Fuel Rod No ⁽¹⁾	Nominal Rod O.D. (inches)	Clad Wall Thickness (mil)	Material Lot ⁽²⁾	Nominal Fuel Pellet Dia. (inches)	Nominal Diametrical Cold Gap ⁽³⁾ (mils)	Unsupported Plenum Length (ins.)	w/o U ²³⁵ Enrich- ment
21	1	0.380	9.7	A	0.357	3.5	0.336	5.69
21	13	0.380	9.7	A	0.357	3.5	0.327	5.69
21	14	0.380	9.7	A	0.357	3.5	0.316	5.69
21	15	0.380	9.7	A	0.357	3.5	0.292	5.69
21	22	0.380	9.7	B	0.357	3.5	0.260	5.69
22	2	0.380	9.7	A	0.357	3.5	0.236	Spiked ⁽⁴⁾
22	4	0.380	9.7	B	0.357	3.5	0.263	Spiked ⁽⁴⁾
22	6	0.380	9.7	A	0.357	3.5	0.241	Spiked ⁽⁴⁾
22	12	0.380	9.7	B	0.357	3.5	0.248	Spiked ⁽⁴⁾
22	19	0.380	9.7	A	0.357	3.5	0.236	Spiked ⁽⁴⁾

NOTES:

(1) Rods were fabricated to a tolerance of $40.000'' \pm 0.026''$

(2) See Appendices A & B.

(3) The gap atmosphere was air introduced during the fabrication operation.

(4) First 14 pellets 5.69%, next 2 pellets 7.3%, next 3 pellets 6.81%, next 12 pellets 6.46%,
next 3 pellets 6.81%, next 2 pellets 6.73%, next 14 pellets 5.69%.

TABLE II

DATA SUMMARY OF THIN-WALLED STAINLESS STEEL CLAD RODS

Fuel Assy. No.	Fuel Rod No.	Calc. Max. Heat Flux (Btu/hr-ft ²)	Calc. Max. Burnup (2) (MWD/MTU)	Calc. Max. Integ. Fast Expos. (1,3) (NVT)	Mtl. Lot (4)	Unsupport Plenum Length (inches)	Deform In Unsupp. Plenum Area	Longit. Ridge Observ. Visual.	Max. Ridge Height (5) (inches)	Post- Irradia- Length (6) (inches)
21	1	410,000	8900	1.1×10^{21}	A	0.336	Yes	Yes	-	-
21	13	410,000	8900	1.1×10^{21}	A	0.327	Yes	No	0.005	40.990
21	14	410,000	8900	1.1×10^{21}	A	0.316	No	Yes	0.020	41.008
21	15	410,000	8900	1.1×10^{21}	A	0.292	No	No	-	-
21	22	410,000	8900	1.1×10^{21}	B	0.260	Yes	Yes	0.013	-
22	2	150,000	3200	4.0×10^{20}	A	0.236	No	No	-	-
22	4	150,000	3200	4.0×10^{20}	B	0.263	Yes	(7)	-	-
22	6	150,000	3200	4.0×10^{20}	A	0.241	Yes	No	-	-
22	12	150,000	3200	4.0×10^{20}	B	0.248	Yes	Yes	-	-
22	19	150,000	3200	4.0×10^{20}	A	0.236	No	(7)	-	-

NOTES:

- (1) At the region of axial peak flux.
- (2) Calculated from CS-137 analysis.
- (3) Peak integrated fast exposure (> 1 mev).
- (4) See appendix B for material properties.
- (5) Ridge height taken as maximum difference between maximum and minimum diameter at a given cross-section.
- (6) Rods were fabricated to a drawing tolerance of 40.000 ± 0.026 .
- (7) Rods were not removed from subassembly and could not be clearly observed.

Table III

Maximum Thin-Walled Clad Stresses and Estimated Material Yield Strength for
Beginning of Life and End of Life Over Pressure Conditions

	<u>Maximum Circumferential Stress⁽¹⁾</u>	<u>Material Lot No. B</u>	<u>Yield Strength Lot No. A</u>
Beginning of Life (2)	-87,600	56,000	72,000
End of Life (3)	-83,800	84,000	108,000

NOTES:

- (1) Elastic calculation, worst clad and pellet dimension tolerance combination.
- (2) Coolant pressure = 2395 psi
Clad temperature = 522°F
- (3) Coolant pressure = 2560 psi
Internal pressure = 300 psi
Clad temperature = 515°F

Transverse Section

250X

Longitudinal Section

250X

Photomicrographs of Lot "A" Thin-Walled
Stainless Steel Cladding

Figure 1

Transverse Section

250X

Longitudinal Section

250X

Photomicrographs of Lot "B" Thin-Walled
Stainless Steel Cladding

Figure 2

SAXTON SPECIAL REMOVABLE FUEL ROD

Figure 3

End Closure Design for Thin-Walled
Stainless Steel Cladding

Figure 4

Typical Weldment of Thin-Walled
Stainless Steel Cladding

Figure 5

3.3X

35X

35X

Typical Fillet Configuration of Welds on Thin-Walled
Stainless Steel Cladding

Figure 6

MODIFIED SAXTON REMOVABLE 3 X 3 ASSEMBLY

Figure 7

**FUEL BEARING PORTION OF
THE SAXTON MODIFIED REMOVABLE
3 X 3 SUB-ASSEMBLY**

Figure 8

#104 ZR (N.R.)	#15 S.S. (R)	#101 ZR (N.R.)
#14 S.S. (R)	#22 S.S. (N.R)	#13 S.S. (R)
#103 ZR (N.R.)	#1 S.S. (R)	#102 ZR (N.R.)

#108 ZR (N.R.)	#12 S.S. (R)	#106 ZR (N.R.)
#6 S.S. (R)	#19 S.S. (N.R.)	#4 S.S. (R)
#107 ZR (N.R.)	#2 S.S. (R)	#105 ZR (N.R.)

Legend

ZR - Zircaloy Clad
 S.S. - Stainless Steel Clad
 R - Removable Rod
 N.R. - Non-Removable Rod

PLAN VIEW OF THE SAXTON CORE ILLUSTRATING THE LOCATION OF THE MODIFIED 3x3 SUBASSEMBLIES

FIGURE 9

SAXTON MAIN COOLANT CHEMISTRY - 1963

Figure 10

Figure 11 Saxton Operating History 1963

SPECIAL 3 X3 ASSEMBLY FOLLOWING REMOVAL FROM THE SAXTON CORE

Figure 12

VISUAL EXAMINATION SUMMARY - REMOVABLE
STAINLESS STEEL CLAD FUEL ROD #13

Figure 13

VISUAL EXAMINATION SUMMARY - REMOVABLE
STAINLESS STEEL CLAD FUEL ROD #4

Figure 14

Figure 15

**CROSS SECTION OF
THIN WALLED STAINLESS STEEL CLAD
AT THE
REGION OF MAXIMUM CRUD DEPOSITION**

Figure 16

BUCKLING OF THIN-WALLED STAINLESS STEEL CLAD IN THE UN-SUPPORTED REGION OF THE FISSION GAS PLENUM

3.3X

Figure 17

Gamma Scan - Fuel Rod #14
Figure 18

TRANSVERSE SECTION ILLUSTRATING FRETTED AREA OF THIN-WALLED STAINLESS STEEL CLADDING

Figure 19

**TRANSVERSE SECTION OF THIN WALLED STAINLESS STEEL
CLADDING ILLUSTRATING LONGITUDINAL RIDGE**

6.6 X

250 X

Figure 20

BUCKLING OF THIN-WALLED STAINLESS STEEL CLAD IN THE UN-SUPPORTED REGION OF THE FISSION GAS PLENUM

Figure 21

APPENDIX A

Chemical Analysis of 304 Stainless Steel Tubing Used to Fabricate the Thin-
Clad Rods

I. Chemical Analysis

<u>Element</u>		<u>Analysis</u>
Carbon	C	0.06
Manganese	Mn	1.03
Phosphorus	P	0.026
Sulfur	S	0.025
Silicon	Si	0.60
Nickel	Ni	9.47
Chromium	Cr	18.30
Cobalt	Co	0.065
Iron	Fe	Bal.

APPENDIX B

Mechanical Properties of Thin-Walled Stainless Steel Cladding

<u>Heat No. 82122 Lot B</u>	<u>Room Temperature</u>		<u>Elevated Temp. 725°F</u>	
	<u>Vendor</u>	<u>Pgh. Testing Co.</u>	<u>Vendor</u>	<u>Pgh. Test.</u>
0.2% offset yield stress (psi):	77,300 - 81,800	66,200 - 75,700	51,400	47,300 - 49,450
Ultimate Strength (psi):	104,400 - 106,200	96,500 - 97,700	78,100	72,100 - 72,650
Elongation in 2 inches (%):	40.0 - 48.0	45.5 - 48.0	27.0	24.0 - 27.5
Average Knoop Hardness at 1 Kg Load:	230			
Grain Size: ASTM 6/7				

<u>Heat No. 82122 Lot A</u>	<u>Room Temperature</u>		<u>Elevated Temp. 725°F</u>	
	<u>Vendor</u>	<u>Pgh. Testing Co.</u>	<u>Vendor</u>	<u>Pgh. Test.</u>
0.2% offset yield stress (psi):	83,700 - 84,600	81,000 - 90,300	---	60,000 - 65,450
Ultimate Strength (psi):	107,200 - 110,000	102,600 - 103,500	---	78,750 - 79,300
Elongation in 2 inches (%):	40.0 - 45.0	37.0 - 40.0	---	20.0 - 24.0
Average Knoop Hardness at 1 Kg. Load:	250			
Grain Size: ASTM 6/7				

Appendix C

Flow Diagram for the Fabrication of the Modified Removable 3x3 Fuel Assemblies

APPENDIX D

Metallographic Sample Preparation

The fuel rod sections to be metallographically examined were pressure mounted in one-inch mounts. The mounts were made by pouring a mixture of epoxy resin, Hysol 6020 and Type A hardener over the sample in a teflon mold. The mounting was done in a pressure vessel which was first evacuated with a mechanical roughing pump and then backfilled with argon to a pressure of 500 psi. After four hours at room temperature, the pressure was reduced to atmospheric and the mounts allowed to cure at room temperature for 12 hours. This mounting technique completely impregnates the cracks and open voids in the UO_2 with the epoxy compound and enables the samples to be polished without loss of UO_2 .

The metallographic preparation consisted of wet grinding the mounted sample in automatic holders using 45 to 60 lbs. pressure on successively finer papers through 600 grit. The samples were then automatically polished using 14 micron diamond paste. Final polishing was performed with Linde-B using distilled water as a carrier. A pressure of 40 lbs. is used for the first five minutes of the final polishing. The pressure was then reduced to 20 lbs. for the final two minutes of the final polish.

The samples were immersion etched in a solution of 60 parts by volume concentrated H_2SO_4 plus 40 parts of 30% H_2O_2 for study of the UO_2 structure. The 304 stainless steel clad samples were etched in a solution of 30 cc HCl and 10 cc HNO_3 which had been aged one day prior to use. The etching time was approximately five seconds.