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OXIDE FUEL ELEMENT DEVELOPMENT
QUARTERLY PROGRESS REPORT
FOR THE PERIOD ENDING JUNE 30, 1969

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U. S. Atomic Energy Commission
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Submitted to AEC-NYOO in August 1969

NOTICE

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INTRODUCTION

This is the fourth quarterly progress report and covers the work performed during the fourth quarter of fiscal year (FY)-1969.

SUMMARY OF OBJECTIVES

The overall program approach is to conduct parallel analytical and experimental studies on mixed oxide fuel pins with close liaison and feed-back between the two activities. In the analytical work, the initial efforts will be directed to compiling all pertinent data on the irradiation behavior of austenitic stainless steel clad, mixed oxide fuel pins. A similar effort will be directed toward compiling data on the behavior of Type 316 austenitic stainless steel cladding - in particular on high-burnup fuel pins. These data will be analyzed by current theoretical models, and where required, new models and computer codes will be devised. These analytical techniques will be used to provide the technical basis for the experimental irradiation programs. This procedure, in turn, will permit reliable parametric studies of design variables of interest to FFTF and LMFBFR.

SUMMARY OF CURRENT PROGRESS

A summary of current progress is shown below. Detailed progress is reported in the individual task sections of this document.

Under Task OFAA-110, project administration and day-to-day liaison with the customer continued. The FY-1970 work program was submitted to the AEC.

Under Task OFAA-210 analysis of clad swelling data for solution treated Type 304 Stainless Steel continued. The range of applicability was extended to temperatures greater than 550°C. The OLYMPUS IB code was selected as the model to be currently used for design purposes. This version can use either the Westinghouse - PNL agreed clad swelling equation or the Westinghouse F-2 equation. Improvements in the code are now in progress. The development of a fuel lifetime code was continued with emphasis on evaluating the mechanical models in CYGRO. Literature reviews and data analyses were initiated on a study of the effects of irradiation on the creep strength of stainless steels with particular emphasis on Type 316.

Under Task OFAA-310, detailed thermal and nuclear design of the two 19-capsule subassemblies was begun. Approval-in-principle of this program has been received from the AEC. It is desired to obtain the highest cladding temperatures possible in this experiment using a standard assembly. A formal request has been made to ANL for permission to slightly exceed the operating criteria of EBR-II, 1200°F, maximum capsule surface temperature and 1000°F, maximum coolant outlet temperature. Work continued on the design of the 37-pin subassembly.

Under Task OFAA-410, procurement specifications for stainless steel materials were prepared or adapted from existing specifications and requests for quotes were issued. The response from prospective manufacturers was very limited principally because of the close dimensional tolerance requirements and the small quantities involved. Fabrication development materials were procured and welding trials were conducted.

Under Task OFAA-510, work was begun at UNC on the 93% enriched fuel. All pellets were fabricated at 93% enrichment and of nominal 89 and 91% theoretical density. Fabrication of UO_2 insulator pellets was initiated at WARD. Twelve of the fourteen glove boxes and the transfer tunnel have been delivered and installed. Ten of the glove boxes have been completely assembled and leak tested and have met the leak testing requirements.

OFAA-110 - PROJECT ADMINISTRATION

A. E. Duval, W. B. Heubel, P. Murray

OBJECTIVES

The objectives of this task are to assure that the project objectives are accomplished on schedule, within budget, and to the satisfaction of the Atomic Energy Commission; to assure compliance with contracted obligations; and to coordinate this project with other AEC-sponsored and Westinghouse sponsored LMFBF development projects.

PRIOR WORK

Authorization for work in FY-1969 was received from the Commission based on the work program submitted in June, and contract modifications 9 through 14, which funded work through FY-1969, were received and executed. Internal work authorizations and budgets were established based on RDT's directions of July 24. The FY-1969 work program, WARD-3791-24, was revised and issued.

During the period, program status and plans were thoroughly reviewed and updated for the remainder of the fiscal year. The mid-year review package of revised plans and cost estimates was completed and forwarded to AEC-NYO on January 7. Shop orders and IWR's were updated to reflect the mid-year status. Work began on the FY-1970 work program.

CURRENT PROGRESS

Project administration and day-to-day liaison with the customer continued. The FY-1970 work program was submitted to the AEC.

OFAA-210 - ANALYTICAL STUDIES OF OXIDE FUEL ELEMENT BEHAVIOR

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B. McHugh, E. D. Shuoa, T. P. Soffa

OBJECTIVES

The maximum utilization of expensive and limited irradiation test data is achieved by a continuing theoretical analysis of the data. The objectives of this task are to provide analyses of the effects of irradiation on deformation mechanisms, fracture mechanics, and structure of cladding materials and the interrelationship of these processes with the stresses imposed by fuel swelling. The technical approach involves the development of theoretical models and appropriate computer codes. The basic objective of this program is to provide an understanding of the behavior of stainless steel clad, oxide fuel elements exposed to fast neutron flux.

PRIOR WORK

The clad swelling equations for Type 304 Stainless Steel presented in earlier quarterly reports were reviewed, and it was decided to use only PNL and ANL immersion density data from within ± 10 inches of the EBR-II core mid-plane. This limitation removed data points with large estimated errors in the calculation of fluence and temperature. Descriptions of work in progress on the OLYMPUS and CYGRO fuel performance codes were presented. An evaluation was made of the creep and stress rupture properties of annealed and cold worked Type 316 Stainless Steel.

CURRENT PROGRESS

Analysis of Stainless Steel Swelling Data

The analysis of clad swelling data for solution treated Type 304 Stainless Steel was continued during this report period. The range of applicability of the design equations given in previous reports has been extended to temperatures in excess of 550°C. Much of this work was performed in conjunction with the materials staff at Battelle Northwest Laboratory (PNL), and the current agreed upon design equation is as follows:

$$\% \Delta V/V = 5.0 \times 10^{-36} (\phi t)^{1.66} \left[\exp \left(\frac{-6800}{RT} \right) - 1.87 \times 10^4 \exp \left(\frac{-27,000}{RT} \right) \right] \quad (1)$$

where: ϕt = fluence for $E > 0.1$ Mev

T = temperature in °K

R = gas constant 1.987 cal/mole °K

$\Delta V/V$ (max) = 12% (saturation)

and $\Delta V/V$ can not be negative

The following criteria were established in order to select swelling data for use in the analysis.

- a. Use only immersion density data as this technique is considerably more accurate than estimating void volume by electron microscopy.
- b. Use only those data obtained from material within ± 10 inches of the EBR-II core mid-plane. Data from the blanket were excluded because of uncertainty in the fluence values and because the spectrum can vary considerably in short distances within the blanket.
- c. Exclude immersion density data measured in apparatus which required specimens five inches long to achieve accuracy. In these cases, the temperature and fluence variations along the specimen would be considerable, and the quoted values may not have much relevance to the measured density change.
- d. Use fluences calculated or corrected by PNL for spectrum according to axial position in the core.
- e. Subtract 0.05% $\Delta V/V$ from all $\Delta V/V$ values based on the PNL hypothesis that some mechanism other than void formation is causing a 0.05% decrease in the density of ST 304 stainless steel subjected to a flowing sodium environment.

The resultant 28 PNL and ANL data points were fitted to an equation of the form:

$$\Delta V/V = A (\phi t)^n \exp (-Q/RT) \quad (2)$$

by a multiple least squares regression analysis which gave the values:

$$A = 5.0 \times 10^{-36}$$

$$n = 1.66$$

$$Q = 6800 \text{ cal/mole}$$

The fluence dependence of ST 304 swelling is shown in Figure 1; development of the equation shown is described below.

The initial method used to describe the temperature dependence of swelling at $T > 550^\circ\text{C}$ was to apply empirical F-factors to the equations obtained by multiple regression analysis. Two such factors were used to obtain estimations of the maximum and minimum swelling to be expected at high temperatures. The equation obtained for ST 304 is:

$$\Delta V/V = 5.0 \times 10^{-36} (\phi t)^{1.66} \exp (-6800/RT) (F) \quad (3)$$

where: $F_2 = \cos (.009 (T-720))$ and $F=1$ for $T < 720^\circ\text{K}$

$F_3 = \cos (.00628 (T-773))$ and $F=1$ for $T < 773^\circ\text{K}$

and $\Delta V/V$ can not be negative.

Figure 1 Fluence Dependence of Types 304 and 316 Stainless Steel

These equations are shown on Figure 2 with the ST 304 data points normalized to a fluence of 5×10^{22} by

$$\Delta V/V (5 \times 10^{22}) = \left(\frac{5 \times 10^{22}}{\phi t} \right)^{1.66} \times \Delta V/V (\text{measured}) \quad (4)$$

The numbers beside the points give the original fluence values and the filled in data points are those used in the regression analysis.

Subsequently WARD and PNL agreed that on the basis of the swelling data at $T > 480^\circ\text{C}$ and from considerations of the annealing behavior of voids that the temperature of maximum swelling would be expected to be $600\text{--}650^\circ\text{C}$ and that swelling would approach zero at $\sim 750^\circ\text{C}$. This approach is believed to be conservative and also show agreement with some of the GE data which indicate significant swelling at 650°C . A "force-fit" of the equation to this predicted behavior yielded equation (1). This equation is plotted for $\Delta V/V$ as a function of temperature in Figure 2 and is seen to be similar to the F3 factor previously used at WARD.

This equation is plotted for $\Delta V/V$ as a function of temperature in Figure 2 and is seen to be similar to the F3 factor previously used at WARD.

Code Development

OLYMPUS

During this report period the basic version of the code (designated OLYMPUS IB) was selected as the model to be currently used for design purposes. This version can utilize the W-PNL agreed clad swelling equation for ST 304 stainless steel or the W F-2 equation (see description of clad swelling analysis above).

Improvements in the code are now in progress. Modifications have been chiefly concerned with the form of the hot-pressing equation used in the code. In the OLYMPUS IB version the equation is:

$$\sigma = \frac{k}{\Delta B} \ln \left(\frac{P_o}{P_B} \right) \quad (5)$$

where σ is the hoop stress generated in the cladding by fuel swelling, P_o is the initial porosity, P_B is the porosity after the interval of burnup ΔB , and k is a constant related to the modulus of rigidity of the fuel. Because P_B , the porosity at burnup B , is dependent upon the additional voidage in the pin arising from clad swelling, it is found that the values of k required to fit the experimental data have a dependence upon the clad swelling relationship used.

It is realized that the burnup rate is not constant but varies with Q , the linear heat rating, hence a time step, Δt , has been substituted for ΔB in equation (5). Additionally the porosity at the beginning of the time step, P_1 , is not necessarily equal to the initial porosity in the

Figure 2 Temperature Dependence of Type 304 Stainless Steel Swelling

fuel pin because of the diametral growth of the pin due to clad swelling. Consequently equation (5) is now written as:

$$\sigma = \frac{k}{\Delta t} \ln \left(\frac{P_1}{P_2} \right) \quad (6)$$

where Δt is a time step and P_1, P_2 are the initial and final porosities for the time step.

Development of a new set of k values, required to be consistent with these changes and with revisions in clad swelling correlations, is in progress. The complexities introduced by the modifications require a sub-routine to establish new k values.

The treatment of cladding behavior is being improved by altering the original assumption of an abrupt transition from no creep to the maximum creep rate at a critical stress level and using instead a gradual increase in creep with increasing stress.

CYGRO

The continued development of a fuel lifetime code based on CYGRO was postponed while the mechanical models in CYGRO were evaluated. The question arose as to the accuracy of the modified plane-strain model in CYGRO upon application to LMFBR fuel. The high thermal gradient across the fuel pellets was expected to be creating conditions beyond the capability of the model. Thus a study was undertaken to evaluate this problem.

Two mechanical codes AGC and FEATS^[1] were used to analyze a typical LMFBR fuel pellet with a radial thermal gradient of 27,000 °F/in. (6000°C/cm). The fuel pellets currently considered have height to diameter (H/D) ratios of approximately unity, but other heights were chosen to effect H/D ratios of 0.71, 1.43, 2.86, and 5.72. The AGC code was used for an axisymmetric, and thus three dimensional, analysis of the pellets. FEATS was used to obtain plane stress and plane strain solutions as two dimensional approximations of the pellets. From the latter the accuracy of the modified plane strain model was determined.

The study determined that under the imposed thermal gradient, pellets with H/D ratios less than 2.0 could not accurately be represented with a plane strain or modified plane-strain model. Table 1 shows the deformation and outer hoop stresses obtained, the modified plane-strain being determined as the axisymmetric solution on the axial mid-plane of pellets with H/D ratios greater than 2.0. Figure 3 shows the variation of the axial stress across the axial mid-plane and Figure 4 the variation of the outer hoop stress axially, both as functions of the H/D ratio. The results obtained were for elastic stress-strain relations only, but the codes indicated that during plastic flow, the deformations changed only by a few percent, the stresses, however, were relaxed by a factor of 10.

Upon completion of the exploratory analysis of the mechanical models in CYGRO, it was decided that the CYGRO code will be used in its present form with the understanding that the limitations in the mechanical model, for LMFBR pellets of H/D=1, are acceptable considering uncertainties in oxide mechanical properties including cracking.

Table 1

Summary of the Displacements and Hoop Stresses at Inner and Outer Radii

	Pellet Inside Radius	Pellet Outside Radius
Plane Strain	$\delta R/R = 2.17\%$ $\sigma_H = -236,000 \text{ psi}$	$\delta R/R = 2.35\%$ $\sigma_H = 285,000 \text{ psi}$
Modified Plane Strain	$\delta R/R = 1.70\%$ $\sigma_H = -224,000 \text{ psi}$	$\delta R/R = 1.87\%$ $\sigma_H = 292,000 \text{ psi}$
Plane Stress	$\delta R/R = 1.67\%$ $\sigma_H = -116,115 \text{ psi}$	$\delta R/R = 1.82\%$ $\sigma_H = 201,000 \text{ psi}$

Fundamental Swelling Behavior

The swelling model used in CYGRO is not satisfactory for the typical LMFBR operating conditions. The precise reason for its failure is not clear, but is probably related to the very high thermal matrix stresses that result from high specific ratings. The application of a tensile stress to a gas bubble will cause it to grow by vacancy acquisition, but above a critical stress, the bubble becomes unstable and will continue to grow to an infinite size.

Alternate methods of analysis or limiting criteria are required in the code to handle bubble instability as irradiation experience shows that gross swelling does not occur in oxide fuels.

The Greenwood-Speight^[2] model for gas bubble nucleation and growth has been critically reviewed and combined with real gas laws using the model of Barnes and Nelson^[3].

The next development stage of this model is to determine the stability of bubble populations under specific operating conditions. When a bubble becomes large enough, it will become mobile and will move towards the center of the fuel under the driving forces of temperature and stress gradients. The large bubbles developed at high temperatures will be the first to be effectively lost so that the large volume increases indicated by the Greenwood-Speight model should not be realized.

Figure 3 Variation of Axial Stress in Axial Mid Plane of Fuel Pellet for Various H/D Ratios and Modified Plane Strain

3274-1

Figure 4 Variation of Hoop Stresses in Outer Annulus as Function of Axial Position
3274-2

A statistical treatment of this problem of bubble migration and its effects on swelling forms the basis of a fuel behavior model*. The model predicts a limiting volume increase which is dependent on local operating conditions. From the preliminary information available, a system describing limiting swelling in terms of temperature, temperature gradient and stress has been developed and is being prepared for computer evaluation. It will be possible to combine this model with the modified Greenwood-Speight model to form a CYGRO subroutine, or for use in a new WARD fuel performance code.

Effects of Irradiation on the Creep Strength of Annealed and Cold Worked Stainless Steel

Literature reviews and data analysis were initiated on a study of the effects of irradiation on the creep strength of stainless steels with particular emphasis on Type 316. General evidence indicates that out-of-reactor creep of Type 316 is controlled by dislocation locking and climb of dislocations. Examination of post-irradiation secondary creep rate data^[4,5] obtained at 550 to 700°C on solution-treated 316 stainless steel shows:

1. At 650°C, there is little or no acceleration of secondary creep in solution treated samples irradiated at 300 - 700°C at fast fluences up to $3 \times 10^{22} \text{ n/cm}^2$.
2. At 700°C, there is apparent evidence of an acceleration of secondary creep (about an order of magnitude) for solution treated samples irradiated at 550 - 700°C at fast fluences up to $1.7 \times 10^{22} \text{ n/cm}^2$.
3. At 550°C, there is apparent evidence of an acceleration of secondary creep (about an order of magnitude) for 20% cold worked samples irradiated to a fast fluence of $3 \times 10^{22} \text{ n/cm}^2$.

Preliminary review of the data and associated experimental scatter and uncertainties, does not lead to definite conclusions regarding effects of irradiation on creep in stainless steels. There is a need for experimental data on the in-reactor creep rate of stainless steels at temperatures between 400 and 650°C and stresses from 5,000 to 20,000 psi. Data of this type is required for design of fuel pins and assemblies.

* H. R. Warner - Private Communication

OFAA-310 - OXIDE FUEL IRRADIATION TEST

A. Biancheria, A. A. Bishop, R. Borst, R. K. Dawless, F. C. Engel,
B. L. Harbourne, P. J. Levine

OBJECTIVES

The overall objectives of this task are to plan, conduct, and evaluate in-reactor experiments of critical areas of special sensitivity to fuel rod behavior analysis and fuel rod assembly performance. The work is being conducted under Subtasks A and B.

Subtask A - Encapsulated Fuel Pin Irradiation Tests

The major objectives of this subtask are to:

- a. define irradiation test programs,
- b. develop materials design data,
- c. design irradiation test fuel pins,
- d. conduct irradiation tests, and
- e. evaluate irradiation test results.

Data and models developed under Task OFAA-210 will be utilized in this subtask and in Subtask B.

Subtask B - Unencapsulated Fuel Pin Irradiation Tests

The objectives of this subtask are to design, irradiate, and evaluate grid-type subassemblies with unencapsulated mixed oxide fuel pins for the purpose of:

- a. demonstrating satisfactory performance of 316 stainless steel grid-type subassemblies in a fast reactor environment;
- b. investigating the combined effects of radiation, flowing sodium, stress, and temperature on the mechanical and corrosion properties of grid materials and on pin-grid interaction; and
- c. developing statistically significant design information on oxide fuel pin performance.

The grid-type subassembly is further intended to provide an irradiation vehicle for fuel pins which will minimize the interaction between individual pins.

PRIOR WORK

Subtask A - Encapsulated Fuel Pin Irradiation Tests

A 34-pin void deployment program was designed. Eight further pins containing axial spacers fixed to the cladding were also identified. The pins are proposed for irradiation in Mk A-subassemblies in positions 6n3 and 7n4. Four of the spacer pins will form part of a higher power subassembly in position 5n2. Approval-in-principle of the program was requested. Negotiations were initiated for the supply of fuel and cladding.

Preliminary pin design indicated that the target operating conditions were attainable, and that spacers could be operated satisfactorily at lower ratings.

Subtask B - Unencapsulated Fuel Pin Irradiation Tests

The prior work on this subtask was primarily directed toward parametric analyses and establishment of a preliminary design for a subassembly to operate in an EBR-II Row 4 position. Preparation of subassembly design drawings was initiated. Bypass flow and sub-channel analyses were started to assist in the final selection of the design and operational parameters. Subassembly experiments in DFR were analyzed for background information on stainless steel grids. A parametric analysis of an unencapsulated 61-pin subassembly was performed to determine the feasibility and capability of irradiating such a design.

CURRENT PROGRESS

Subtask A - Encapsulated Fuel Pin Irradiation Tests

Void Deployment Pin Design

Detailed thermal and nuclear design of the two 19-capsule subassemblies was begun and will be completed during the next quarter. By selective positioning of pins within the subassembly to balance void deployment parameters against flux gradient, constancy of power generation to less than 5% variation has been attained. Constancy of temperatures between subassemblies will be obtained by using the same coolant flow rate in each. This may require a non-standard size orifice in one assembly.

Actual peak power generation rates are shown in Tables 2 and 3. The location of each pin within the subassembly is shown in Figure 5 for W-1 and Figure 6 for W-2.

Hot channel factors have been calculated using available manufacturing tolerances and standard EBR-II uncertainty factors. These are presented in Table 4. Two types of total hot channel factors are shown. The statistical factors result from a statistical combination of all the subfactors. The traditional factors are the result of a combined statistical-multiplicative method. The factors dealing with fuel

Table 2

Pin Details, Subassembly WSA-1

EBR-II Position 6n3

Pin No.	Fuel				Clad			Peak Rating	Target Clad	Target Burnup	Exposure
	ρ_s	ρ_t	gap	% U-235	Type	Wall Thickness	Inside Diam.	(kW/ft)	Temp. (°C)	(a/o)	(Mwd.)
1	93	95	1-3	43	ST	10	.200	6.2	500	3.0	12,500
2	89	91	1-3	43	ST	12.5	.200	6.2	500	3.0	12,500
3	93	95	1-3	43	CW	12.5	.200	6.2	500	3.0	12,500
4	85	91	5-7	43	ST	10	.200	6.0	500	5.0	20,000
5	93	95	1-3	43	ST	12.5	.200	6.1	500	5.0	20,000
6	85	91	5-7	43	CW	12.5	.200	5.9	500	5.0	20,000
7	89	91	1-3	43	CW	12.5	.200	6.1	500	5.0	20,000
8	93	95	1-3	43	ST	10	.223	8.4	540	3.0	12,500
9	89	91	1-3	43	CW	10	.223	8.5	540	3.0	12,500
10	93	95	1-3	43	ST	12.5	.223	8.4	540	3.0	12,500
11	89	95	5-7	43	ST	10	.223	8.4	540	5.0	20,000
12	85	91	5-7	43	CW	10	.223	8.2	540	5.0	20,000
13	93	95	1-3	43	CW	10	.223	8.3	540	5.0	20,000
14	89	91	1-3	43	ST	15	.223	8.3	540	5.0	20,000
15	89	95	5-7	43	ST	10	.223	8.2	540	5.0	20,000
16S	93	95	1-3	43	ST	10	.200	6.0	500	3.0	12,500
17S	89	91	1-3	43	ST	12.5	.200	6.0	500	5.0	20,000
18S	93	95	1-3	43	ST	12.5	.223	8.3	540	5.0	20,000
19S	89	91	1-3	43	ST	10	.223	8.1	540	5.0	20,000

Table 3
Pin Details, Subassembly WSA-2
EBR-II Position 7n4

Pin No.	Fuel				Clad			Peak Rating	Target Clad	Target*	Exposure
	ρ_s	ρ_t	gap	% U-235	Type	Wall Thickness	Inside Diam.	(kW/ft)	Temp. (°C)	(a/o)	(Mwd.)
1	93	95	1-3	65	CW	10	.200	6.1	500	3.8	15,000
2	89	91	1-3	65	ST	15	.200	5.9	500	3.8	15,000
3	85	89	3-5	65	ST	12.5	.200	6.0	500	6.4	25,000
4	89	91	1-3	65	CW	10	.200	6.1	500	6.4	25,000
5	93	95	1-3	65	ST	12.5	.200	6.1	500	6.4	25,000
6	89	91	1-3	65	CW	10	.200	6.1	500	6.4	25,000
7	89	95	5-7	93	ST	10	.200	8.3	540	5.0	15,000
8	93	95	1-3	65	ST	12.5	.223	8.2	540	3.8	15,000
9	89	91	1-3	65	CW	12.5	.223	8.1	540	3.8	15,000
10	85	89	3-5	65	ST	10	.223	8.2	540	6.4	25,000
11	89	91	1-3	65	ST	12.5	.223	8.4	540	6.4	25,000
12	85	89	3-5	93	ST	15	.200	8.1	540	6.4	25,000
13	93	95	1-3	65	CW	12.5	.223	8.2	540	6.4	25,000
14	93	95	1-3	93	ST	10	.223	9.3	570	4.0	15,000
15	89	95	5-7	93	CW	12.5	.223	8.9	570	4.0	15,000
16	89	95	5-7	93	ST	10	.223	10.9	570	8.2	25,000
17	93	95	1-3	93	CW	12.5	.223	11.8	570	8.2	25,000
18	85	89	3-5	93	ST	10	.223	8.1	570	8.2	25,000
19	85	91	5-7	93	CW	12.5	.223	10.1	570	8.2	25,000

* At mid-plane

Figure 5 Subassembly W-1 Desired Position in EBR-II 6n3

Figure 6 Subassembly W-2 Desired Position in EBR-II 7n4

Table 4

EBR-II Uncertainty Factors for WARD Capsules

	Uncertainty Factor						
	Coolant Enthalpy	Coolant Film	Capsule Wall	Capsule Bond	Fuel Clad	Fuel Clad Gap	Fuel Pellet
<u>Fuel Deviations</u>							
Pellet Diameter	-	1.005	1.005	1.005	1.005	1.005	1.005
Pellet Density	-	1.011	1.011	1.011	1.011	1.011	1.011
U+Pu Wt. Percent	-	1.001	1.001	1.001	1.001	1.001	1.001
Pu in U+Pu	-	1.022	1.022	1.022	1.022	1.022	1.022
Fissile Pu in Pu	-	1.001	1.001	1.001	1.001	1.001	1.001
Fissile U in U	-	1.001	1.001	1.001	1.001	1.001	1.001
Statistical Deviation	1.0165	1.025	1.025	1.025	1.025	1.025	1.025
<u>Dimensional Deviations</u>							
Capsule and Shroud	-	1.03	1.05	-	-	-	-
Bond	-	-	-	1.022	-	-	-
Clad	-	-	-	-	1.11	-	-
<u>Thermal Properties</u>							
Capsule Conductivity	-	-	1.10	-	-	-	-
Sodium Conductivity	-	1.04	-	1.04	-	-	-
Clad Conductivity	-	-	-	-	1.10	-	-
Fuel Kdt	-	-	-	-	-	-	1.10
Sodium Heat Capacity	1.02	-	-	-	-	-	-
Heat Trans. Correlation	-	1.20	-	-	-	-	-
Gap Conductance	-	-	-	-	-	1.20	-
<u>Neutron and Gamma Flux Distribution</u>	1.07	1.10	1.10	1.10	1.10	1.10	1.10
<u>Coolant Flow Variations</u>							
Total Subassembly Flow	1.05	1.010	-	-	-	-	-
Dist. Within Subassembly	1.064	1.005	-	-	-	-	-
<u>Power Level Variations</u>							
Level Measurement	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Transient Overload	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Traditional Factor	1.33	1.38	1.39	1.28	1.47	1.45	1.33
Statistical Factor	1.12	1.24	1.16	1.12	1.19	1.23	1.15

variations are combined statistically and the result multiplied by the remaining factors to obtain the total traditional factor. All analyses have used the more conservative traditional hot channel factors.

It is desired to obtain the highest cladding temperatures possible in this experiment using a standard assembly. While lower temperature will result in a good experiment, the higher temperatures will provide a more sensitive test of the fuel pin model and provide more useful data on cladding swelling. At a given power level, cladding temperatures may be maximized by reducing the coolant flow rate until an EBR-II limiting criterion is reached. Figure 7 is a plot of nominal clad surface temperature versus flow rate for several pins. Three pin lengths are considered for the 11.75 kW/ft pin.

The two operating criteria that must be observed are:

- a. the maximum capsule surface temperature under hot channel conditions may not exceed 1200°F, and
- b. the coolant outlet temperature of the subassembly must be less than 1000°F, or within 100°F of that of adjacent assemblies.

The first criterion may be relaxed if the experimenter can demonstrate to the satisfaction of EBR-II that the capsule will operate safely. Some relaxation of the second criterion may be permissible at low flow rates if there is adequate coolant mixing below the core cover plate to avoid structural thermal stresses. Until these criteria have been clarified, two design options will be retained. These are detailed in Table 5. Option B is preferred as it gives the higher cladding temperatures while still meeting the requirement of coolant temperature < 1000°F. Cladding temperature profiles for the two cases are shown in Figure 8.

Mechanical design will proceed with the two options, but with emphasis on option B as representing the more severe operating conditions. The reduction in fuel length required by option B affects only six pins and will reduce the reactivity of the subassembly by less than 10%.

Crimp trials were initiated to aid in establishing the proper crimp tooling design and to provide information for design analysis. Details of the tests are reported under Task OFAA-510.

Materials, Supplies, and Pin Fabrication

The first fuel pellets containing 93% U-235 have been fabricated by United Nuclear Corporation and are being inspected. Additional details are given under Task OFAA-510. Cladding for this program will be delivered in two or three weeks.

WARD-AEC-ANL Negotiations

Approval-in-principle of this program has been received from the AEC. Telephone discussions with ANL (Idaho) on the relaxation of thermal criteria have indicated that either option A or B would be acceptable. A formal request has been made to ANL for permission to operate under these conditions.

Figure 7 Nominal Clad Surface Temperature vs Flow Rate (gpm)

Table 5
Thermal Design Options

Option No.	Peak Rating (kW/ft)	Coolant Flow (gpm)	Nominal Clad T. (°F)	Hot Spot Capsule (°F)	Coolant WSA-2 (6n3) (°F)	Outlet T. WSA-2 (6n3) (°F)	Fuel Length (in.)
A	6.2	17.2	940	965	923	946	14.2
	8.5	17.2	1021	1062			14.2
	11.75	17.2	1148	<u>1206</u>			14.2
B	6.2	13.0	1003	1048	<u>996</u>	<u>994</u>	14.2
	8.5	13.0	1107	1177			14.2
	11.75	13.0	1141	1197			10.2

NOTE: Underlined temperatures exceed EBR-II basic criteria

i.e. Maximum capsule temperature † 1200°F
6n3 coolant temperature † 979°F
7n4 coolant temperature † 957°F

Figure 8 T clad Surface Temperature vs Length

Notice has been received of a proposed increase of 25% in EBR-II power level. A preliminary evaluation has indicated that the increase would be acceptable with the subassemblies relocated further out in the core. Re-orificing would probably be required.

Subtask B - Unencapsulated Fuel Pin Irradiation Tests

Subassembly Design

The potential unavailability of high priority row 4 space in EBR-II necessitated a change in experimental plans to design and analyze for a row 5 position. The basic design parameters presented last quarter[6] and recalculated values for row 5 are summarized in Table 6 for comparison. The reduced flow rate, higher clad temperature, and lower power rating are the result of the change in position.

The bypass flow analyses described last quarter have been completed for the dimple-type grid and design modifications were made. The grid support strap design now incorporates tabs at the top to block peripheral channel flow, as shown in Figure 9. It has been calculated that this tab will reduce bypass flow from 10% to less than 3% with a 5 mil clearance between the tab and adjacent strap. Final clearances will be established on the basis of the completed thermal analyses. In addition to the tab modification, the liner has been extended up into the grid support strap region, as shown in Figure 10, to reduce bypass flow between the strap and inner can. This change should reduce this bypass flow from 5-7% to less than 2% on the basis of the worst combination of tolerances.

The reduced length of fuel pin shown in the table is the result of incorporating neutron shielding at both ends of the fuel bundle as required by the EBR-II project. One method of incorporating shielding is to place two stainless steel plugs just above the fuel pin with peripheral herringbone grooves for coolant flow and using a standard EBR-II Mark J-19 subassembly lower end fitting at the bottom. Another method of shielding being considered is the placement of metal slugs above and below the fuel column inside the pin cladding. This design would use the longer pin length. The former design was analyzed to characterize the pressure drops expected at the inlet and outlet ends of the subassembly. Using equations of the form

$$\Delta_p = \frac{A_p V^2}{2g} + \frac{B_V^{0.2} V^{1.8}}{2g} \quad (7)$$

with the 39.9 gpm flow rate for row 5, the combined pressure drop was calculated to be 6.5 psi for 700°F inlet and outlet temperatures, respectively.

In order to determine the number of grids and spacing required in the 37-pin subassembly, analyses of potential rod deflections induced by thermal gradients were started. Several techniques described in the literature were examined for suitability and ease of use. A search for test data to substantiate the selection of an analytical method was initiated.

Table 6

Comparison Design Data for 37-Pin Subassembly

EBR-II POSITION	4n2	5n2
A. DIMENSIONS		
1. Pellet Diameter, in.	0.0195	0.191-0.198
2. Clad Inside Diameter, in.	0.200	0.200
3. Outside Diameter, in.	0.230	0.230
4. P/D	1.24	1.24
5. Distance Between Outer Rod and Liner, in.	0.022	-
6. Inside Distance Across Flats, in.	1.755	-
7. Total Pin Length, in.	60.875	41.875
B. THERMAL PARAMETERS		
1. Average Coolant Outlet Temp. °F	1000	1000
2. q' peak in. max. rod, kW/ft	13.03	12.44
3. q' peak in. avg. rod, kW/ft	-	-
4. q' peak in. min. rod, kW/ft	11.82	10.53
5. q' avg. in. avg. rod, kW/ft	10.84	10.25
6. Max. Clad Surface Temp. (1000°F Outlet), °F	1188	1211
7. Nuclear Radial Form Factor	1.046	1.089
C. HYDRAULIC PARAMETERS		
1. Number of Grids	10	6-10
2. Grid Strap Thickness	0.010	0.010
3. Grid Height, in.	0.50	0.50
4. Assembly Pressure Drop (Allowable)	34.5	34.0
5. Max. Free Stream Velocity, ft/sec	12.5	-
6. Average Free Stream Velocity, ft/sec	11.97	11.4
7. Orificing is Required for 1000°F Outlet	-	-
8. Flow Rate GPM	42.15	39.9

Figure 9 Grid Assembly Details for 37 Pin Subassy

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Figure 10 37 Pin Subassembly Grid-Liner Profile Detail

Works by McAreavey[7], WARD[8], and Rapier, et al[9] were reviewed. Procedures and equations of the latter appear to be the most suitable for use in this program. The WARD computer program (FATBO 2)[8] not adaptable to single rod analyses, will be used for final overall bundle calculations. Rapier's equations were modified to include effects of axial loads on the grids due to pin-grid friction. Using nominal flow and temperature values for the 37-pin subassembly, the amplification of the initial (cold) bow by thermal gradients and additional axial loads of 0.3 lbs per grid were calculated. Figure 11 shows the preliminary results. It appears that if the maximum allowable amplification is set at 3/2, the maximum grid spacing will be about 5-1/2 inches. These analyses are being continued to provide final values for the design.

The grid strap tooling design was completed with final approved drawings to be available early in July. Fabrication quotes will be solicited by mid-July with a target completion date in late August. Grid support strap tooling designs are near completion. A preliminary design of a rig to load and unload fuel pins remotely in the subassembly was completed. Finalization of this design was postponed until all subassembly and hardware designs are completed.

Experimental Design

The experimental program for the fuel pins was established on a statistical basis to provide information on void deployment and pin performance relative to subassembly position. This can be done because no interference between fuel pin and grid will occur during reactor exposure. Since the cladding will be the same size for all pins (0.230-inch O.D. x 0.200-inch I.D.), deployment of fuel pin voidage will be accomplished by varying pellet densities and diameters. Four conditions that will be studied are:

<u>Smear Density</u>	<u>Pellet Density</u>	<u>Diametral Gap - Inch</u>
93%	95%	0.002
90%	95%	0.005
87%	95%	0.009
87%	90%	0.003

The fuel will be solid pellets of $(U_{.75}Pu_{.25})O_2$ helium-bonded to the 20% cold-worked 316 stainless steel cladding. The uranium will be fully enriched in U-235.

In addition to the void deployment variation, subassembly position was considered in the pin arrangement because of 1) the flux gradient across the subassembly and 2) the potential influence of different thermal conditions in various channels on pin and grid performance. Therefore, the subassembly was divided into two halves - the 18 pins nearest the core centerline and those furthest from the core centerline. Within each half of the subassembly, four groups of pin locations were designated in an attempt to isolate effects of different channel characteristics.

Figure 11 Preliminary Calculations of Thermally Induced Bowing and the Effect of Grid Friction by Rapier's Method

The four locations are:

1. Outer hex corners
2. Outer hex faces
3. Mid hex positions
4. Inner hex positions

The proposed arrangement of 37-unencapsulated pins in a 5n2 core position is shown in Figure 12. Each pin is identified, by symbol, for one of the four void deployment conditions. The calculated linear power ratings at mid-plane are also shown for the latest recommended fission rate distribution. These ratings range from 10.5 to 12.5 kW/ft. Specific pin parameters are listed in Table 7 for a target peak burnup of 5%.

The above parameters were combined with temperature distributions obtained from the LETHAL code and put into the OLYMPUS IB (see Task 210) code to evaluate the total strain on the maximum and minimum power pins in the subassembly. The prime purpose of this exercise is to determine the start-of-life dimensions for the grid cells on the basis that the fuel pin will just contact the grid dimples at the end-of-life for the maximum case. Initial results with cold worked grids and cladding operating to 5% burnup at 12.5 kW/ft in a 5n2 position indicate a total 1.6% $\Delta D/D$ in the pin of which 1.25% is clad creep. Since this exceeds a design limit of 1% allowable clad creep strain, fuel pin parameters will have to be modified slightly. The evaluation of parameters is continuing with the most current developments of Task 210.

Figure 12 Subassembly Plan for 5n2 Position

Table 7

Pin Details for WARD Unencapsulated Subassembly WSA-3

Pin Number	Density %		Pellet Diameter Inch	Gap Inch	Linear Power Ratings kW/ft	
	Smear	Pellet			Peak	Average
1	90	95	0.195	0.005	12.25	10.89
2	87	90	0.197	0.003	11.79	10.48
3	87	95	0.191	0.009	11.64	10.35
4	93	95	0.198	0.002	12.44	11.06
5	93	95	0.198	0.002	12.46	11.07
6	90	95	0.195	0.005	12.03	10.69
7	87	90	0.197	0.003	11.56	10.27
8	87	95	0.191	0.009	11.42	10.15
9	87	90	0.197	0.003	11.45	10.18
10	90	95	0.195	0.005	11.90	10.58
11	93	95	0.198	0.002	12.22	10.86
12	90	95	0.195	0.005	11.79	10.48
13	87	95	0.191	0.009	11.26	10.01
14	87	90	0.197	0.003	11.30	10.04
15	87	95	0.191	0.009	11.13	9.90
16	87	95	0.191	0.009	11.23	9.98
17	90	95	0.195	0.005	11.67	10.38
18	93	95	0.198	0.002	11.98	10.65
19	90	95	0.195	0.005	11.56	10.27
20	93	95	0.198	0.002	11.86	10.54
21	90	95	0.195	0.005	11.44	10.17
22	93	95	0.198	0.002	11.72	10.42
23	87	95	0.191	0.009	11.01	9.79
24	87	90	0.197	0.003	11.06	9.83
25	87	95	0.191	0.009	10.93	9.72
26	90	95	0.195	0.005	11.33	10.07
27	93	95	0.198	0.002	11.63	10.34
28	90	95	0.195	0.005	11.21	9.96
29	87	90	0.197	0.003	10.89	9.68
30	87	95	0.191	0.009	10.76	9.56
31	87	90	0.197	0.003	10.80	9.60
32	90	95	0.195	0.005	11.10	9.87
33	93	95	0.198	0.002	11.39	10.12
34	87	95	0.191	0.009	10.60	9.42
35	93	95	0.198	0.002	11.32	10.07
36	90	95	0.195	0.005	10.93	9.72
37	87	90	0.197	0.003	10.52	9.35

OFAA-410 - FABRICATION DEVELOPMENT OF EBR-II SUBASSEMBLIES

E. C. Bishop, D. N. Elliott, W. E. Ray

OBJECTIVES

The objectives of this task are to develop fabrication procedures and produce 37- and 61-pin EBR-II subassemblies based on the PFR honeycomb grid design. The scope of this program will be limited to grids, cans and end fittings with fuel pins being prepared under Task OFAA-510.

The subassembly fabrication effort, covered by this task, will include the following:

- a. establish optimum welding parameters for grid fabrication;
- b. determine the optimum welding procedures for fabrication of can seam welds and can-to-grid joints;
- c. determine fabrication and assembly procedures for attaching any fittings required to support and locate the subassemblies in EBR-II;
- d. prepare simulative samples of all joints and evaluate the effects of fabrication and heat treatment operations on the mechanical properties of the joints;
- e. identify suitable inspection criteria for assessing the subassembly components;
- f. fabricate simulative models for design verification testing;
- g. fabricate subassemblies for insertion in EBR-II; and
- h. identify post-irradiation examination procedures and parallel out-of-pile control grid tests to facilitate grid performance evaluation.

PRIOR WORK

During the last reporting period, Type 316 SS strip was welded by electron beam, ultrasonic, and resistance processes to evaluate these techniques for grid fabrication, with resistance welding identified as the reference method. Concurrently, specific requirements for a suitable resistance welding machine were discussed with several manufacturers. Techniques for attaching the grids to the inner can were also considered and TIG spot welding was

identified as the reference process for this application.

CURRENT PROGRESS

Equipment (Procurement not funded under this contract)

A purchase order was placed with Sciaky for a 50KVA Resistance Welding Machine capable of making both spot and projection welds at currents between 200 and 28,000 amps. All timing functions on this machine are digitally controlled to assure good repeatability of welding conditions and delivery of the machine is scheduled for early July 1969.

A Miller ESR-150 TIG welding machine was procured and installed at WARD for TIG welding fabrication under Contract AI(30-1)-3791. In addition to the standard timer module, measuring seconds, a cycletimer module was also procured to provide control during TIG spot welding. The two machines described above provide the basic welding equipment required for fabrication of the 37-pin subassemblies. The equipment and techniques presently being used by WNFD for subassembly fabrication and inspection are being reviewed for their applicability to the present program and surplus equipment availability is being established. In addition, a list of dimensional inspection equipment requirements has been compiled and procurement has been initiated.

Materials

Materials selected for the major subassembly structural components are as follows:

1. Inner grid straps - 316 SS, 20% cold-worked, 0.010 in. thick x 0.5 in. wide
2. Outer grid support strap - 316 SS, 20% cold-worked, 0.010 in. thick
3. Inner can - 304 SS, annealed with final straightening pass, 2.000 in. outer flat dimension x 0.040 in. wall hexagonal tubing
4. Liners - 304 SS, 20% cold-worked, 0.020 in. thick strip to be formed into hexagonal tubes with outer flat dimension of 1.015 in.
5. Outer can - 304 SS, annealed 2.289 outer flat dimension x 0.040 in. wall hexagonal tubing i.e., standard EBR-II outer can.

Procurement specifications for these materials were prepared or adapted from existing specifications, and requests for quote were issued. The response from prospective manufacturers was very limited, principally because of the close dimensional tolerance requirements and the small quantities involved.

Grid Straps

Hamilton Precision Metals was the only supplier to provide a positive response to requests for quote on grid strap materials. Even in this

case, exceptions were requested to the relevant specification (ARD-AMMA-030-3), on the following five items:

1. liquid penetrant testing
2. surface appearance
3. nitrogen content
4. identification markings
5. clearing solution composition.

These requested exceptions have been negotiated as follows:

1. liquid penetrant testing will be performed by WARD
2. poor surface appearance, which is obviously closely linked to item (1), will be a basis for rejection; material exhibiting laps, cracks and deep scratches will not be accepted.
3. the nitrogen content specified by WARD (0.01 - 0.03%) will be adhered to by selection from various heats at an additional cost of \$75 per order.
4. individual strips will not be marked with their identification until they are received at WARD.

Alternate suppliers have been contacted since the initial requests for quote were issued but none of them surpassed Hamilton in meeting the relevant WARD specification. Consequently, purchase orders have been placed with Hamilton for all grid strap materials.

Inner Can

The initial requests for quote yielded only one company, namely Carpenter Technology, that was interested in supplying the inner can. They quoted on cans made by forming and welding strip materials and indicated that a special heat would be required to conform with the chemical composition specification. Carpenter proposed that this special melt would be made at their mill in Reading, Pa. Because of the high cost and long deliver (28-32 weeks) required by this supplier, alternate approaches have been tried to expedite this procurement, as described below:

1. Obtain standard EBR-II cans and if necessary make slight modifications to the subassembly design to accommodate size discrepancies or re-work EBR-II cans to the required dimensions.
2. Compromise the initial procurement specification to avoid the necessity of a special melt.
3. Increase dimensional tolerances to enable smaller tooling changes.

The most promising approach to date appears to be a combination of (2) a and (3) above, and both Carpenter Technology and Pneumatic Tool Corporation are preparing quotes with a view to decreasing the cost and improving the delivery indicated previously.

Outer Cans

It was originally expected that ANL would supply WARD with outer cans, but they have recently reported that they have insufficient cans available to do so at the present time and suggested that quotes should be obtained from companies that already have the required tooling. These quotes have been requested.

Liners

Requests for quote are being obtained for strip to produce liners by forming and welding, and, for completed hexagonal tubing.

Fabrication Development Materials

For the purpose of fabrication development materials, strips of similar thicknesses to specific subassembly components have been procured using standard ASTM specifications, thereby, avoiding any unnecessary delay in this program.

Welding Trials

Weld test samples simulating the outer grid strap to inner can joint have been made with 100% joint strengths in a rotary clear test. Major parameter variations have been studied for this joint and are being evaluated by both metallography and lap shear tests. Details of this study will be reported in the reset period when the full range of results are available.

Simulative inner grid straps have been prepared so that grid straps have grid fabrication development can be started as soon as the Sciaky resistance welding machine is installed during July 1969.

OFAA-510 - FABRICATION OF OXIDE FUEL PINS

P. M. French, R. K. McGeary, R. Paris, B. Riley

OBJECTIVES

The objectives of this task are:

- a. To identify a process capable of fabrication of mixed uranium and plutonium oxide fuel of the required geometric, stoichiometric, and physio-chemical properties to meet the objectives of Task OFAA-310. The fuel will be essentially $(U_{0.8}Pu_{0.2})O_{1.98}$ in the form of pellets 0.2 inch in diameter of 90 to 95% TD. This objective will include the writing of a process description, a materials description, and the identification of all necessary support analytical determinations in the control of process variables.
- b. To identify certain characterization parameters necessary to complement the fabrication process outlined in (a) and the irradiation program OFAA-310; i.e., thermal conductivity, expansion, etc.
- c. To fabricate mixed uranium-plutonium dioxide fuel pellets for all phases of the contract work and irradiation program.

PRIOR WORK

Detailed specifications for procuring fuel pellets were prepared in conjunction with the work conducted under Task OFAA-310. Fuel pellets for the void deployment irradiation tests described under Task 310 (identified as subassemblies WSA-1 and WSA-2) will be obtained from an outside supplier. The specifications were sent to the supplier for review and comments. Agreement has been reached on all changes suggested by the fabricator and on the test procedures to be employed. Standards for porosity, plutonium distribution, and pellet integrity remain to be prepared by the supplier and mutually agreed upon. These latter items will not delay initiating pellet fabrication.

CURRENT PROGRESS

Fissile Material Procurement

It has been agreed to receive the PuO_2 from Hanford after calcination at 400°C rather than 700°C which was considered necessary to produce the powder in the desired form. This was necessary because 400°C is the standard production treatment and acceptance of this material would expedite delivery. It is planned to recalcine the material after receipt at the laboratory.

Twenty kg of natural UO_2 has been received and twenty kg of 93% enriched UO_2 was ordered with delivery expected in mid-August.

A visit was made to UNC to determine the status of the characterization and fabrication of $(\text{U}, \text{Pu})\text{O}_2$ fuel pellets for the encapsulated pins. Work was initiated on the 93% enriched material. All pellets have been fabricated at the 93% enrichment and of nominal 89 and 91% theoretical density. The remaining pellets having a 93% enrichment have been pressed and will be sintered during the first week of July. At this time UNC hopes to ship all the pellets of the above enrichment on the scheduled date. The powders for the 65% enriched material have been mixed and test sinters initiated.

Fabrication of UO_2 Insulator Pellets

Preliminary mix-milling and cold-pressing trials on the natural UO_2 was initiated. An assessment will be made of the impurity pick-up and pressability of the powder after various milling times using WC balls.

Construction of the WARD device for tube crimping has been completed and has been tried on 0.250-inch O.D. x 0.010-inch wall tubing. The contour on the pinching jaws was not to specification so the jaws were sent back to the vendor for rework. After reinstallation the jaws did not pinch the tubing uniformly. An empirical approach is being used to dress and back-relieve the edges of the jaws in order to get a uniform crimp. In addition, the contour of the groove in the discs initially set by design engineering does not appear great enough. Additional discs of various groove dimensions are being prepared for crimping trials.

Considerable planning has been completed for adaption of pin loading and disc crimping to the actual glove box operation. A modified "udder-bag" technique will be used.

WARD Plutonium Oxide Laboratory

Of the fourteen glove boxes that comprise the Plutonium Oxide Laboratory, twelve boxes and the transfer tunnel have been delivered and installed in the facility. Ten of the glove boxes have been completely assembled and leak tested and have met the leak testing requirements. The eleventh and twelfth boxes are complete and the transfer tunnel is presently under leak test and should be completed by early July. All boxes will require a final check to verify that all the components have been provided and will then be given a complete clean-up before final acceptance from the vendor.

Of the two outstanding glove boxes, the centerless grinder and weld boxes will be installed and leak tested by mid-July.

Of the major pieces of equipment to be installed within the glove boxes, the automatic pellet press, calcination furnaces, and centerless grinder have been delivered and installed. The remaining major item, the high temperature sintering furnace, is presently under construction at the vendor's plant with completion expected by the middle of July. According to present schedules, fabrication trials on mixed oxide fuel materials are planned for August 1969.

The general layout of the glove boxes within the laboratory is shown on Figure 13 and a photograph of the transfer tunnel and glove box line is shown in Figure 14.

Figure 13 General Layout ARD Pu Oxide Laboratory

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Figure 14 Transfer Tunnel and Glove Box Line of WARD Plutonium and Oxide Laboratories

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