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FUEL ELEMENT STUDY

FOR REACTOR OVERBORE PROGRAM

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J. T. Stringer

W. A. Blanton

December 15, 1960

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FUEL ELEMENT STUDY FOR REACTOR OVERBORE PROGRAM

INTRODUCTION

Recent studies¹ have confirmed that large incentives exist for overboring the reactor process channels approximately 500 mils in the C and five old reactors under the proposed Plant Improvement Program. Conservative estimates of the incentives for overboring indicate a payout period of about two years for the proposed work, an increase in plutonium production of 15-18%, derived from increased conversion ratio and a reduction in plant unit cost. Since sufficient progress has been made in the areas of reactor development to warrant the necessary planning and budgetary action to accomplish the proposed work, a preliminary study has been conducted to determine and assess the technical problems associated with the processing and performance of oversize fuels, to define those areas requiring further development, and to provide cost estimates for the conversion and operation of both offsite uranium fabrication facilities and HAPO fuel manufacturing facilities as required to produce oversize fuel elements. Details of this study are contained in this report.

SUMMARY

The proposal to overbore the graphite channels approximately 500-550 mils in one or more of the present Hanford reactors will require fuel elements about 0.5" larger in diameter than the present I & E fuel elements. Oversize fuel loadings are planned to be a 50-50 mixture of natural and enriched (0.94% U-235) fuel elements with the possibility of using a uniform enrichment of about 0.82% U-235. At the proposed reactor operating conditions of 95 C bulk outlet water temperature, maximum specific powers in the order of 105-110 KW/ft. will be generated in oversize fuels during winter months. Surface temperatures will be in the range of 135-140 C. Under these conditions, maximum central uranium core temperatures of 360-395 C will be attained.

Under the proposed reactor operating conditions, it is difficult to predict the performance of self-supported AlSi canned, oversize I & E fuel elements without having had any experience with fuels of this size. The incidence of jacket corrosion and end closure ruptures is not expected to be any higher for oversize fuels than for the present I & E fuel designs irradiated under similar conditions, except for the possible effects of doubling the in-reactor residence time for oversize fuels on surface corrosion of the cladding. Higher stress levels in oversize I & E uranium cores, resulting from an increase in cross-sectional area, may ultimately reach a level where cleavage ruptures could occur. Calculated

1 HW-66823, "Major Overboring of C Reactor". E. C. Wood, E. R. Astley, J. H. Brown, and L. W. Lang. October 6, 1960. (Secret)

stress levels within oversize cores are in the range of 70,000 psi, which falls between that calculated for the present I & E geometry (51,000 psi) and that at which cleavage failures were experienced in the solid fuel geometry (90,000-100,000 psi). If a cleavage threshold is reached, stress levels can be reduced by increasing the oversize I & E core ID or through the use of alternate fuel geometries such as the rod-in-tube and tube-in-tube configurations.

An AlSi canned fuel element is proposed for oversize fuels, with an alternate possibility of using the hot-press or gas pressure diffusion bonded process in the event the AlSi process proves limiting under proposed reactor operating conditions. At the present time, it is not believed that the AlSi process will be limiting. However, tests are in progress to evaluate possible limitations of AlSi-bonded fuels at high power and exposure. These tests are scheduled for completion by the end of CY 1961. Preliminary tests will also be completed on the aforementioned alternate processes during the same period.

Although alpha-phase rolling is currently the standard method for fabricating uranium rods from ingot and dingot bars for subsequent machining into core blanks, beta heat treating, and finishing to core dimensions, alpha-phase extrusion is being evaluated and may prove to be a satisfactory and economic alternate. Both rolling and extrusion technology will be carried forward for the fabrication of regular and oversize fuels. Ingot uranium used in the fabrication of oversize fuel cores will probably contain small amounts of iron and silicon as controlled additions to achieve grain refinement, which has been established as standard practice for alloyed dingot uranium. At the time significant quantities of oversize cores are required, uranium heat treating improvements currently under development will be incorporated in the process to produce a more uniform, dimensionally stable product.

The aluminum jacketing material for oversize fuels will be X-8001 alloy or a newer alloy providing increased corrosion resistance. Accelerated hot spot type corrosion will be minimized through the use of self-supported fuels in ribless process tubes. Because of the added weight of oversize fuels, development of suitable self-support rail designs will be required.

If an AlSi brazed fuel element proves to be non-limiting, the present lead-dip process will be used to assemble oversize fuel elements. Before sizable quantities of oversize fuels are required, process improvements to minimize braze porosity and achieve a more uniform, homogeneous, strong Al-AlSi-U bond will be in use. Most of the problems in AlSi canning are expected to be related to the equipment necessary to handle and process oversize fuels approximately 0.5" larger in diameter and twice the weight of present fuels. In addition, process development will be required to optimize canning conditions.

Capital and operating cost estimates are presented below for producing oversize fuels under the following combinations of reactor overboring:

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- Case 1 C Reactor only overbored; 50-50 mixture of natural and 0.94% U-235 enriched uranium.
- Case 2 C plus 5 old reactors overbored; 50-50 mixture of natural and 0.94% U-235 enriched uranium.
- Case 3 All reactors overbored; 50-50 mixture of natural and 0.94% enriched uranium.
- Case 4 Same as Case 3 except a uniform uranium enrichment of 0.82% U-235 is assumed.

ESTIMATED CAPITAL COSTS TO CONVERT FACILITIES TO OVERSIZE FUELS

	Dollars			
	Case 1	Case 2	Case 3	Case 4
Uranium Feed Sites	650,000	4,000,000	4,000,000	1,500,000
Fuel Manufacturing Facilities	750,000	2,000,000	*2,000,000	*2,000,000
Total	1,400,000	6,000,000	6,000,000	3,500,000

* Equipment flexibility provided by Case 2 is essentially adequate for Cases 3 and 4.

COMPARISON OF ESTIMATED FPD OPERATING COSTS FOR STANDARD
AND OVERSIZE I & E SELF-SUPPORTED FUEL ELEMENTS

	Standard 8" I&E*	Oversize 8" I&E*	Standard 6" I&E**	Oversize 6" I&E**	Oversize 8" I&E***
Fuel Dim. & Wt.					
OD (Inches)	1.464	1.991	1.458	1.991	1.991
ID (Inches)	0.375	0.339	0.375	0.339	0.339
Length (Inches)	8.965	8.865	6.640	6.540	8.865
Uranium Wt. (Lbs.)	7.320	14.970	5.290	10.820	14.970
Est. FPD Mfg. Costs (100% Yield)					
Process Material	\$1.82	\$2.00	\$1.85	\$2.03	\$2.00
Operating Labor	0.47	0.70	0.47	0.70	0.70
Overhead	1.94	3.64	1.94	3.64	3.64
Conversion Cost/Pc.	\$4.23	\$6.34	\$4.26	\$6.37	\$6.34
Depreciation	\$0.40	\$0.75	\$0.40	\$0.75	\$0.75
Total Cost/Pc.	\$4.63	\$7.09	\$4.66	\$7.12	\$7.09
Total Cost/Lb.	\$0.63	\$0.47	\$0.88	\$0.65	\$0.47

* Natural U
 ** 0.94% Enriched
 *** Uniformly Enriched to 0.82%

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It will be noted that the above fuel element manufacturing costs are based on 100% finished fuel element yield for ready conversion to actual yield levels. Present I & E fuel element yields approximate 86% and oversize fuel yields should ultimately approach this level. Incremental costs (labor and material) will be about 15% higher for oversize fuels.

Estimates provided by the Feed Materials Division, Oak Ridge Operations Office, of annual increases in feed material site operating costs resulting from the fabrication of oversize fuel cores for the various cases are as follows:

	Dollars			
	Case 1	Case 2	Case 3	Case 4
Annual Increase-Feed Site Operating Costs	100,000	2,400,000	2,600,000	3,900,000

The above increases in estimated feed site operating costs reflect the increased cost of fabricating the additional tonnages of enriched and natural uranium required for oversize fuels over and above the tonnages forecast in the FY 1965 production forecast.

Development effort at the feed material sites and in FPD will be required to support the production of an optimum quality oversize fuel element. The estimated development manpower required is shown below for the production of an AlSi bonded oversize fuel element. Should it be necessary to develop an extended surface fuel element or utilize an alternate process such as diffusion bonding, the development time required would be about doubled.

	Man-Years			
	Case 1	Case 2	Case 3	Case 4
Feed Sites	2	3	3	3
Fuel Assembly	3	5	6	6
Total	5	8	9	9

One man-year of development effort is estimated to cost about \$50,000 and includes indirect charges, supporting services, and material.

DISCUSSION

Basic Assumptions

The basic assumptions in this study were as follows:

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1. Process tube channels in the C and five old reactors will be overbored 500-550 mils.
2. Existing ribbed process tubes in the C and old reactors will be replaced with oversize ribless zircaloy or ribless and/or ribbed aluminum tubes.
3. The K Reactor process tube channels will not be overbored; however, existing process tubes will be replaced with ribless zircaloy or ribless aluminum tubes. (This does not exclude the possibility of overboring of these reactors, since potential incentives exist for overboring in the order of 400 mils.)
4. Schedules assumed for reactor overboring and process tube replacement are as follows:

<u>Reactor</u>	<u>Shutdown Date</u>	<u>No. of Tubes</u>	<u>Approximate Startup Date</u>
C	12/1/62	2000	4/1/63
KE	3/1/64	2400	5/1/64
KW	5/1/64	2400	7/1/64
F	8/1/64	2000	11/1/64
B	2/1/65	2000	5/1/65
D	5/1/65	2000	8/1/65
DR	8/1/65	2000	11/1/65
H	11/1/65	2000	2/1/66

5. Fuel elements for each full reactor loading will be provided at least one month prior to the reactor startup date.
6. Product mix for the C and five old reactors is assumed to be 50% natural uranium and 50% enriched (0.946% U-235). This does not exclude an alternate consideration for using a uniformly enriched fuel in the range of 0.82% U-235.
7. Product mix for the K Reactors will be about 84% natural uranium and 16% enriched (0.946% U-235) uranium.
8. Fuel designs will be essentially as follows for an I & E geometry:

<u>Reactor</u>	<u>Fuel Type</u>	<u>OD (Inches)</u>	<u>ID (Inches)</u>	<u>Length (Inches)</u>	<u>Weight (Pounds)</u>
C	Natural	1.991	0.339	8.865	14.97
	Enriched	1.991	0.339	6.540	10.82
O	Natural	*	*	*	*
	Enriched	*	*	*	*
K	Natural	1.520	0.420	8.865	7.86
	Enriched	1.520	0.420	8.540	5.66

* Assume old reactor fuel size will be about the same as for C Reactor.

- 2 "Plant Acquisition and Construction Budget Preparation, FY1963 and Revision of FY1962". T. H. Lyons. October 4, 1960. (Unclassified)

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9. Based on the above fuel designs, the estimated fuel requirements for each full reactor loading are as follows:

Reactor	Fuel Type (Tons)		Total
	Natural	Enriched	
C	250	250	500
O	250	250	500
K	403	77	480

10. Reactor fuel requirements on a replacement basis, assuming the operating conditions outlined below, will be as indicated:

Operating Conditions	C	O	K
Bulk Outlet Temperature Limit (°C)	95	95	95
Coolant Flow (gpm)	109,000	115,000	200,000
Operating Level (MW)	2,340	2,500	4,375
Exposure (MWD/T)	650-800	650-800	650-800
Operating Efficiency (%)	75	75	75

Reactor Fuel Requirements (Tons/Year)

Reactor	650 MWD/T			800 MWD/T		
	Natural	Enriched	Total	Natural	Enriched	Total
C	495	495	990	400	400	800
O (5)	2750	2750	5500	2140	2140	4280
K (2)	3090	590	3680	2520	480	3000
	6335	3835	10,170	5060	3020	8080

Since exposures have not been optimized for oversize fuel, manufacturing facilities should be capable of producing the tonnages shown above for an exposure of 650 MWD/T. Reactor residence time for the oversize fuel is assumed to be twice that of present loadings, resulting in about equivalent fuel tonnage requirements.

11. The following assumptions apply to oversize fuel elements prepared by the AlSi process:

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- a. Because of increased core weight, manual transfers in canning will be limited to one piece at a time.
- b. Canning cycle - 45 seconds.
- c. Operating efficiency - 90%.
- d. Finished fuel element yield - 70%.
- e. Supports will be welded to all finished fuel elements.
- f. The AlSi product flowsheet will be the same as for projection fuel project CGF-903 and is shown in Fig. 1 of the Appendix.

URANIUM CORE FABRICATION

Technology

The technology for producing hollow uranium cores with an OD of about 2" and an ID of about 0.450" is not expected to be significantly different from present technology for producing I & E fuel element cores. Uranium for oversize fuel cores can be produced by the reduction of green salt to a 300-lb. derby for subsequent recasting under vacuum to an ingot (ingot process) or by the dingot process (reduction of green salt to a 3300-lb. dingot). Based on present reactor performance of ingot and dingot uranium, the choice between the two can only be based on expediency and cost. To date, approximately 200 tons of dingot uranium have been irradiated and no significant difference can be detected in the performance of dingot and ingot uranium.

Fabrication

Fuel cores can be fabricated by alpha phase rolling either ingot or dingot bars to approximately 2" diameter solid rod for subsequent drilling and machining to final size. Or, solid or hollow ingots and dingots can be alpha-phase extruded to solid or hollow rod for subsequent finishing to final size. A third possibility is that of direct casting uranium under vacuum to the approximate finished core dimension followed by finish machining. Of the three possible fabrication routes, rolling and extrusion are the farthest advanced in technology. While direct casting offers significant improvements in cost, the technology is essentially undeveloped and production equipment is not available. Rolling is the method by which all standard fuel cores are produced for the present reactors at HAP0. Some development work will be required to optimize the parameters for producing 100% recrystallization of the coarse-grained ingot or dingot structure, but this is not expected to be a major problem. Alpha-phase extrusion to rough final core size is an alternate route to rolling. Extrusion of hollow cores has the advantage of eliminating the necessity of drilling a solid core and thus reduces the amount of scrap that must be re-cycled. This results in a cleaner and less costly product. HAP0 has irradiated solid extruded fuels and fuels which have been fabricated from uranium extruded in solid form and subsequently drilled. No significant difference between a rolled product and an extruded product could be found. Irradiation experience for a hollow extruded I & E product is lacking at present but over the next year significant

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tonnages are expected to be evaluated and irradiated. Based on extensive comparison of the metallurgical properties of rolled and extruded hollow uranium cores out-of-reactor, no difference in reactor performance is anticipated between the two. Adequate extrusion facilities are available and technology has been extensively developed by Bridgeport Brass Company at Adrian, Michigan. In addition, MCW has facilities available for extruding 2" diameter fuel cores and, in fact, have produced by extrusion the first 1000 cores for the initial 20-tube C Reactor test.

The technology for both alpha-phase rolling and extrusion will be carried forward. Although rolling is currently the prime process candidate for oversize fuel fabrication, extrusion has a high ultimate potential and is handicapped only by a lack of irradiation data.

Metallurgical Properties

The metallurgical properties of uranium that are believed to have the most significant effect on the irradiation performance are the size and uniformity of the grains, the crystallographic orientation, the residual stress in the piece, and the purity (cleanliness) of the metal. Grain sizes coarser than about A-2 (FEDC Grain Size Standard) tend to cause surface bumping in the reactors at high power and exposure. This restricts water flow and if severe bumping occurs, the jacket can be ruptured. Non-uniform grain size throughout the length and cross-section of the core can contribute to warp during irradiation. Beta heat treating has a pronounced effect on the size and uniformity of the grains as does the chemical composition of the metal. Certain elements (Fe, Si, Cr, Al, Zr, and possibly C) have a grain refining effect. Thus ingot uranium having more impurities than dingot and enriched uranium, has a finer grain structure. Grain size control of the uranium is not expected to present any unusual problems. The use of additives (150 ppm Fe and 100 ppm Si) in dingot uranium to refine the grain size has progressed to the point where this technique can be extended to natural and enriched ingot uranium. At present, test quantities of enriched ingot fuel cores containing Fe and Si as additives are being prepared by National Lead for evaluation. By the time significant tonnages of oversize fuels are required, the use of grain refining additives is expected to be standard practice. Grain size measurement has also progressed to the point with the non-destructive UT-2 testers where all production can be tested for grain size and cores rejected for not only large grain, but also non-uniform grain size throughout the piece.

When uranium is worked by rolling or extruding, the grains orient themselves in a preferred manner. Unless the preferred orientation is erased, the uranium warps and distorts during irradiation. Beta heat treating is employed to randomize the crystallographic orientation. Development work will be required to optimize the beta heat treatment of the oversize cores. Because of the larger cross-section, particularly if the piece is heat treated before drilling the hole, the quench rates from the beta phase will be different from current I & E production. Difficulty may be encountered in obtaining a uniform grain

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size from center to outer surface, but this problem is not expected to be as severe if hollow core blanks are heat treated. As a matter of fact, the first 1000 cores for initial C Reactor test have been heat treated in hollow form and appear on the basis of metallurgical examination to have a satisfactory grain size and random orientation. Heat-treating technology is expected to be further advanced as a result of completing currently planned tests on alpha annealing after beta treatment and different quenching media to produce a fine equi-axed grain structure and remove residual stress.

Machining oversize fuel cores to final size is not expected to present any technical problems.

Uranium re-cycle and recovery will present problems to the feed sites. An extrusion process will generate less fine scrap (turnings) than a rolling process. At the present time a standard ingot casting charge consists of 25% virgin derby, 50% solid scrap, and 25% briquettes (the fine turnings). Considerable pressure is currently being exerted on the feed sites by both Savannah River and Hanford to develop scrap recovery processes that permit the recycle of higher purity uranium than it is possible to obtain presently with briquette introduction into the ingot. A number of promising recovery processes are under development at both National Lead and Mallinckrodt and by the time significant quantities of oversize fuel cores are required, it is expected that much cleaner metal will be in production.

Feed Site Costs

The Feed Materials Division of the Oak Ridge Operation Office was requested³ to provide cost estimates (capital and operating) for producing oversize fuel elements for four specific cases as follows:

- Case 1 Conversion of C Reactor only to overbore. 50% natural uranium - 50% of 0.94% U-235 enriched uranium.
- Case 2 Conversion of C and five old reactors to overbore. 50% natural uranium - 50% of 0.94% U-235 enriched uranium.
- Case 3 Conversion of C, five old, and two K Reactors to overbore. 50% natural uranium - 50% 0.94% U-235 uranium.
- Case 4 Same as Case 3 except all uranium would be uniformly enriched to about 0.82% U-235.

The following cost estimates were provided by the Oak Ridge Operations Office⁴ and are based on the use of ingot uranium processed to oversize fuel cores by either a rolling or extrusion process:

-
- 3 HW-67157, "Request for Budget Study". R. L. Dickeman to A. T. Gifford. October 20, 1960. (Secret)
 - 4 HAN-76967, "Budget Estimates for Oversize Fuel Element Production". A. T. Gifford to R. L. Dickeman. November 15, 1960. (Secret)

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		Capital Cost (Dollars)	Increased Operating Cost (Dollars/Year)
Case 1	C Reactor	650,000	100,000
Case 2	C and five Old Reactors	4,000,000	2,400,000
Case 3	C, five Old, and K Reactors	4,000,000	2,600,000
Case 4	Same as Case 3-Uniform Enrichment of 0.82% U-235	1,500,000	3,900,000

The \$650,000 capital cost estimate for Case 1 includes approximately \$200,000 for new lathes, \$200,000 for two new casting furnaces, and \$120,000 for tooling charges to either roll or extrude the larger size rod or tube stock. The \$4,000,000 capital cost for Case 2 and 3 includes estimated costs for assuring the isotopic integrity of the multi-isotopic streams to be concurrently produced at National Lead, of dividing the National Lead metal plant into a separate parallel system for both the reduction and casting steps, of completely separate machining facilities for assurance of segregation of machine turnings, sludges, etc., of mass spectrometers for isotopic control, and for the necessary tooling and machining changes required. The \$1,500,000 capital estimate for converting all of Hanford's present reactor uranium requirements to an oversize fuel with a uniform enrichment of about 0.82% U-235 assumes that Hanford's NPR requirements would be held at the 0.94% U-235 level, that Savannah River's requirements would be normal uranium, and that all SRO Mark V-B elements would be produced at Weldon Spring (MCW).

The increased operating costs shown for the various cases reflects the increased cost of producing the additional tonnages of enriched and natural uranium required for the oversize fuels over and above the tonnages forecast in the FY 1965 production forecast.

ALUMINUM COMPONENTS

Aluminum Cladding Technology

During the past year, X-8001 alloy (21% Ni, 0.5% Fe) has replaced C-64 alloy as the standard fuel cladding alloy. Since intergranular attack of the C-64 alloy is initiated at temperatures in the order of 200 C and in excess of 350 C for X-8001 alloy, it was expected that X-8001 alloy fuel cladding would significantly reduce jacket corrosion ruptures rates. However, severe localized attack of the X-8001 alloy in the form of deep pits and hot spots (accelerated corrosion without evidence of intergranular attack), has continued to contribute

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to cladding ruptures. Cause of the localized pitting of this alloy is unknown, but appears to be associated with certain reactor coolant flow and temperature conditions and/or characteristics of the alloy or its oxide film.

Localized accelerated corrosion of the fuel element cladding surface is largely attributed to coolant flow restrictions resulting from fuel misalignment, eccentric positioning, and warp during irradiation. Projection I & E fuel element tests, including both self-supported fuels in ribless zircaloy and aluminum tubes and "bumper" fuels in ribbed aluminum tubes, indicate that accelerated corrosion (hot spot) failures may be minimized by full-scale conversion to projection fuel loadings.

Uniform surface corrosion of present I & E fuels is becoming more evident with increases in reactor power and bulk outlet coolant temperatures. Two possible routes being investigated for reducing uniform corrosion include: (1) nickel plating of finished fuel element jacket surfaces; and (2) evaluation of new aluminum alloys having potentially improved corrosion resistance. Maximum uniform corrosion rates are currently in the order of 3-6 mils per month.

Overboring of the C and old reactor graphite channels 550 mils, and utilizing X-8001 alloy clad fuels with a proposed OD of about 1.991" and an ID of 0.339", results in a redistribution of heat flux between the inner and outer annulus and a 38% increase in outer jacket surface area. Under present C Reactor operating conditions, the maximum uniform jacket corrosion of oversize fuels in a ribless zircaloy tube having an R value of about 1.05 would be approximately 2 mils per month. Under projected reactor coolant flow, temperature and power conditions listed in the assumptions for this study, the OD of the oversize fuel will probably be reduced to take advantage of increased coolant flow, resulting in a jacket corrosion rate approaching 3 mils per month in ribless zircaloy tubes.

In the case of aluminum ribbed tubes for oversize fuels, rib height presumably would be higher than optimum to obtain economic tube life. Thus, the R values for this type of process tube would approximate 1.15-1.20, resulting in a uniform fuel jacket corrosion rate of about 3 mils per month, and up to 4 mils per month under projected reactor operating conditions.

By limiting maximum uniform surface corrosion of oversize fuel X-8001 cladding alloy to 25 mils, it is concluded that oversize fuels having a minimum residual wall thickness of 30 mils can be irradiated to an exposure of 800 MWD/T (approximately double the residence time for standard I & E fuels) without incurring corrosion in excess of this limit. Prolonged exposures, however, would exceed tolerable corrosion limits unless the guaranteed minimum wall thickness of the fuel cladding is increased.

New Cladding Alloys

At present two aluminum alloys are being investigated as potential alternates for X-8001 alloy. One is C-810 alloy, consisting essentially of X-8001 alloy

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with 0.1% titanium added to refine the secondary phase (more uniform dispersion). The other is an experimental high purity (low silicon) base alloy. Major alloying constituents of X-8001 alloy and the new alloys are listed below:

	<u>Ni</u>	<u>Fe</u>	<u>Ti</u>	<u>Si</u>
X-8001	1.0%	0.5%	--	0.1%
C-810	1.0%	0.5%	0.1%	0.1%
Low Silicon Alloy	1.0%	0.5%	0.1%	0.003%

A series of autoclave corrosion tests on coupons of the X-8001, C-810, and low silicon alloys in refreshed de-ionized water at 360 C have been conducted by the Hanford Laboratory Operation. These tests have indicated that the induction time (transition from a uniform to a high linear corrosion rate) is greater for the new alloys. Based on their potentially improved corrosion resistance, test quantities of components fabricated from both alloys are being procured for in-reactor corrosion tests.

Aluminum Component Fabrication

No unusual problems are foreseen in the offsite procurement and fabrication of X-8001 alloy components for oversize I & E fuels. If alternate alloys are considered, the addition of 0.1% titanium to produce C-810 alloy is not expected to affect component fabrication. Vendor capability of producing large quantities of the low silicon base alloy have not been fully investigated, but may be limited.

A comparison of present I & E X-8001 alloy component costs with estimated oversize I & E X-8001 alloy component costs in quantities of 100,000 pairs (cap and spire) or more are shown below:

<u>Component</u>	<u>Present I & E</u>		<u>Oversize I & E</u>	
	<u>6-Inch</u>	<u>8-Inch</u>	<u>6-Inch</u>	<u>8-Inch</u>
Can	\$0.53	\$0.57	\$0.55	\$0.60
Spire	<u>0.70</u>	<u>0.81</u>	<u>0.74</u>	<u>0.86</u>
Cost Per Pair	\$1.23	\$1.38	\$1.29	\$1.45

The cost of oversize components fabricated from C-810 alloy will be essentially the same as for X-8001 alloy based on preliminary estimates from the vendor. Because of the higher material costs resulting from the production of a low silicon base alloy, the costs of components fabricated from this alloy are expected to be about 20% higher than X-8001 alloy.

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Lead time for manufacturing procurement of oversize aluminum components from the present vendor is approximately 16 weeks. Alternate vendors, undergoing evaluation, indicate the lead time could be reduced to approximately 8 weeks.

OVERSIZE FUEL PREPARATION

AlSi Product Technology

Fuels of both solid and I & E geometry up to a maximum OD of about 1.500" have been successfully produced by the present AlSi process.⁵ Experience in processing larger diameter fuels has been limited to approximately 500 KER-size (1.8" OD) fuel elements, of which about half were of the I & E geometry. Because of the small quantity involved, no attempt was made to optimize process conditions or finished fuel quality. Some of the finished pieces were irradiated in the KER loops; however, operating temperatures and exposures were too low to yield any useful data relative to the performance of oversize I & E fuel elements.

Technical problems associated with the preparation of oversize I & E fuel elements (2.00" OD and 0.340" ID) will be primarily centered around the component cleaning and canning operations of the lead-dip process. Adequate cleaning and deoxidizing of the aluminum components, in combination with optimum preheating cycles and vibration in the AlSi canning assembly baths, are essential to acceptable component wetting. Non-wetting of the aluminum components contributes to both defective end closures and non-uniform thermal conductivity between the fuel element AlSi braze layer and the aluminum cladding during irradiation. Recognizing certain deficiencies in the present component cleaning process, an investigation is being made of potentially improved cleaning and deoxidizing agents, including possible applications of ultrasonic vibration to facilitate cleaning. These improvements will be equally beneficial in the manufacture of either standard or oversize fuels.

The increased mass of the proposed oversize uranium fuel cores, which is essentially double that of present fuel cores, will necessitate optimization of the duplex canning bath preheat cycle in the lead layer, and the reaction time in the AlSi layer. No significant changes in the pre-surface preparation (nitric acid pickle) of the larger cores prior to canning is anticipated. Duplex canning bath cycle times can be readily optimized through a series of statistically designed tests. Core temperatures reached in the duplex bath must be carefully established within narrow limits to insure that the core can be easily inserted into the can-sleeve assembly in the canning bath without excessive erosion of the can-wall. In addition, reaction time in the AlSi layer must be adequate to produce a uniformly strong compound layer over both the internal and external core surfaces. Lead-uranium reaction compounds formed on the core surface during the preheat cycle in the lead layer are subsequently washed off in the AlSi layer through agitation, and a complex

5 HW-57029, "Process Specifications, Fuel Element Manufacturing Process".
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aluminum-silicon-uranium intermetallic compound layer is produced. Studies have shown that the uniformity and strength of compound layers produced in the duplex bath are dependent on temperature, time, silicon content of aluminum-silicon layer, core position, and agitation. Inadequate control of these variables results in either a thin brittle laminar compound layer or the formation of a coarse thick porous layer. Brittle compound layers offer only limited resistance to undercutting, as compared to scrambled tough compound layers containing large amounts of UAl₃-type compound. Identification of compound layers has generally required tedious cross-sectioning of fuel elements and metallographic examination. More recently, however, sufficient correlation has been observed between fuel element bond strength measurements and metallographic data to facilitate process development and control through the use of "stud pulling" techniques to determine bond strength and related compound layer characteristics.

Capacities of the existing induction furnaces used in the canning operation, and operator ability to handle larger cores, may ultimately govern the choice of canning cycles for oversize fuel elements. The canning assembly furnaces are operating near their maximum efficient heating load⁶ for standard size fuel elements on a 45-second cycle. Therefore, necessary adjustments to the overall canning cycle time to accommodate oversize fuels may be accomplished either by canning two pieces at a time on a long cycle (~70 seconds) or by canning one piece at a time on a 30-45 second cycle. Pilot plant evaluation will be required to choose between these two alternatives.

Pilot plant tests will also be required initially to optimize oversize fuel assembly conditions in the AlSi canning baths. Variables contributing to non-wetting of the aluminum components and braze porosity must be adequately controlled. Can-sleeve preheat and submerge cycles must be optimized to assure that the inner surface of the can reaches bath temperature, and adequate vibration is introduced to expel any entrapped gases from the submerged assembly, prior to core insertion. Benefits derived from the adoption of contoured base cans and sleeves to accelerate can base heating rates will apply equally well to oversize fuel components. Minor revisions of the cap-spire preheating cycle and vertical pulsing rates⁷ may be also necessary to assure acceptable cap-spire wetting and the removal of oxide and gas bubbles from underneath the cap wafer.

The quenching of oversize fuel assemblies after canning may require minor changes in present procedures to avoid placing the internal braze in tension during cooling. Pressurized quenching equipment is currently being prototyped for installation on all canning lines. Tests have shown that if 80 psi air pressure is applied to fuel assemblies prior to water quenching, braze porosity is suppressed at least four-fold.

No problems are foreseen in adopting current technology to the finishing of oversize AlSi bonded fuels. Present machine tooling for facing standard size fuels can be readily modified for fuels having a larger diameter. End

6 HW-42056, "Dipping and Canning Furnace Heating Capacities". T. B. Correy. March 2, 1956. (Confidential-Undocumented)

7 HW-65800, "Cap-spire Pulsing". C. A. Burgess. June 15, 1960. (Confidential)

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closure weld quality is largely dependent on the quality of the underlying cap or spire braze. Braze porosity, oxides, and other impurities contribute to defective welds. Recent tests⁸ have shown direct-current welding is superior to alternating-current welding. By comparison, DC welded end closures showed a 44% improvement in braze mixing, combined with a substantial decrease in weld cracking and pinholes. Because of these potential improvements in weld quality, steps are being taken to replace the existing AC power supplies on all production welders with DC power supplies.

Existing non-destructive tests for uranium grain size, can-wall penetration, bond quality, and radiography of end closures, can be readily adapted to testing oversize fuels. The ultrasonic bond testers are currently being converted from 20 megacycles to 25 megacycles to improve reproducibility and sensitivity to non-wet areas and fractured bonds. The lower sensitivity of the 20-megacycle units to these defects may account for some of the larger braze defects observed in irradiated fuels. New non-destructive tests being developed for uranium grain orientation, core surface quality, and finished fuel closure integrity will also be applicable to oversize fuels.

As outlined above, the development effort required to manufacture oversize AlSi bonded fuels primarily involves optimization of the canning process. Much of the initial development can be accomplished in conjunction with a program in progress to demonstrate oversize fuels in 20 C Reactor overbored channels.

Projection Rail Design and Welding Technology

Considering the 550-mil overbore case for the C and five old reactors, rail heights in the order of 70-80 mils will be required for oversize fuel in ribless zircaloy process tubes. Experience to date has been limited to X-8001 alloy collapsible bridge rails, having nominal thickness of 32 mils and a maximum height of 75 and 80 mils, respectively, for the B Reactor ribless aluminum tube facility and the 69 ribless zircaloy tubes installed in C Reactor. Compression tests show that these rails will collapse about 7 mils under a 300-lb. load and collapse completely under a 700-lb. load. Although rails of this design are capable of supporting oversize fuels (twice the weight of present fuels), susceptibility to mechanical damage during handling most likely will warrant an increase in rail thickness to 40-45 mils. Since the length of oversize fuels will be the same as present fuel designs, positioning of the rails both longitudinally and circumferentially (90° apart) on either end of the fuel elements will remain essentially unchanged.

The higher bearing loads of oversize fuels may result in excessive galling between the support rails and process tubes. Galling in zircaloy tubes should not be a serious problem, except for possible damage to the protective oxide film or buildup of aluminum on the load bearing surfaces. Possible remedial

8 HW-66354, "Comparison of AC and DC for Welding Aluminum-Clad Fuel Elements". G. R. Hanson. August 26, 1960. (Unclassified)

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measures include re-design of rail to reduce friction, nickel plating of the rail supporting surfaces, and the use of improved lubricant for reactor charging. Ex-reactor and in-reactor tests will be required to optimize rail designs and resolve any potential problems in this area. If ribbed process tubes are substituted for ribless process tubes in the overbore program, the present solid "bumper" rails or slight revisions thereof can be readily adapted to oversize fuels.

AlSi PRODUCT MANUFACTURING FACILITIES

Conversion of the existing AlSi product manufacturing facility to the production of oversize I & E fuels for the C and old reactors will introduce numerous problems with respect to flexibility and scheduling, particularly during the conversion period. Currently, this facility has adequate capacity to meet existing reactor requirements on a five-day week, two-shift schedule. By maintaining flexibility in both equipment and plant design to reduce setup changes for the different fuel models produced, losses in production have been held to a minimum. Existing equipment is designed to manufacture both solid and I & E fuel elements having a maximum OD of approximately 1-1/2".

Based on the schedules assumed for overboring the C and old reactors, conversion of the fuel manufacturing facility can be most conveniently managed in two phases. The first phase would consist of the equipment modifications and additions required to produce oversize fuels for C Reactor. This phase of the work, as well as the second phase, should be accomplished without reducing plant capacity or otherwise causing undue interruption of the production of other fuels needed to meet reactor requirements. At least five months lead time will be required to prepare the first loading of oversize fuels for C Reactor. Assuming a C Reactor startup date after overboring of April 1963, equipment should be in place to prepare the initial loading not later than November 1962. On or before this date, it will be necessary to place the fuel manufacturing facility on a third shift to meet overall production commitments based on present forecasts.

During the second phase of conversion, maintenance of operating continuity will be at a premium. This phase of the work will consist of an extension of the earlier work to produce oversize fuels for both the C and old reactors, retaining the necessary flexibility to produce 1.5" OD fuel elements for the K Reactors. Minimum lead times for the preparation of each of the initial oversize fuel element loadings for the old reactors are also expected to be in the order of 5 months. Because three-shift operation of the plant will reduce significantly the time equipment is available for maintenance and change-over between fuel models, some increases in standby equipment capacities will be warranted under the final phase of conversion.

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As stated above, existing fuel manufacturing equipment is designed to handle fuel elements having a maximum OD of approximately 1-1/2". Consequently, rather major equipment modifications and additions will be necessary to produce oversize I & E fuels having a maximum OD of about 2". A brief description of these equipment changes is outlined below.

Component Preparation

Existing pairs of aluminum component cleaning, sleeve cleaning, and core pickle machines have adequate capacity for the proposed throughput, with one machine of each type operating and the other on standby. New baskets will be required for the aluminum component cleaning machines and the core pickle machines to accommodate larger components. Modifications of the bare core grain size testers (UT-2) is necessary to handle larger cores. New sleeve trays and additional conveyors to canning area will also be required.

Canning

Because of the increased heating load imposed on the existing canning furnaces by the oversize fuel assembly, as well as the problems introduced in the transfer of heavier pieces, it is assumed that oversize fuels will be canned at a rate of one piece every 45 seconds. Existing duplex bath agitators, duplex loaders, canning jacks, and quenching units, will require modification. Since operation of 6 canning lines on 3 shifts, 5 days a week will be required to meet reactor requirements at projected operating levels and exposures, 2 fully equipped canning lines must be added to insure continuity of operation on this schedule.

Finishing and Testing

Although it is both mechanically and economically feasible to modify existing 6-spindle facing lathes to accommodate fuel elements having a maximum OD of 2", lead times required for factory modification show that immediate scheduling of this work would be required to meet anticipated oversize fuel production schedules. For this reason, it is assumed that it will be necessary to procure four 2" lathes and excess two of four 1.25" lathes. In addition, a 2" single-spindle lathe will be required for the reclamation of oversize fuel weld rejects.

Serial stamping equipment, currently being designed for installation by mid-CY 1961 will only require new dies to accommodate oversize fuel.

Mechanical modification of the 5 existing automatic end closure welders will be required to handle oversize fuels. Three additional automatic welders should be provided to replace older semi-automatic welders. Mechanical handling equipment used in conjunction with 5 existing bond and penetration testers will also require modification to handle oversize fuels.

Penetration etch equipment is scheduled to be converted to an alkaline-detergent etch process under projection fuel project CGF-903. Only new racks will be required to handle oversize fuel.

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A prototype fuel closure integrity tester (UT-4) is currently being evaluated. If adopted for quality control purposes, it is assumed that the required number of units will be installed independent of the oversize fuel program. Only the mechanical system of these testers will require modification for oversize fuel. At this time it is not possible to predict whether the UT-4 testers will replace radiography of fuel element closures. If continuation of radiography is justified, modification of the radiograph trays to handle oversize fuels will be required.

Five ultrasonic rail welders are scheduled for installation under project CGF-903. Modification of the mechanical handling systems of these welders, plus one additional welder, will be required for oversize fuels. Minor modifications will also be required to other auxilliary equipment used in the attachment and testing of projection rails, including baskets for the soap dip prior to welding.

Based on the present 20-hour autoclave testing cycle, 33 autoclaves operating on a 3-shift, 6-day week schedule, will be required to meet production commitments. Operating experience indicates that at least one bank of 6 autoclaves would be needed for backup, warranting the installation of 3 additional autoclaves.

In addition to the above, miscellaneous inspection gages, carts, and modifications to conveyor systems will be required to fully equip the finishing and testing operation to handle oversize fuels.

Slug Recovery

Baskets for the caustic stripper and treater tanks, capable of handling oversize fuel canning rejects, will be required for this operation.

Finished Fuel Storage

Existing storage pallets for finished fuels are specifically designed for present fuel models. New pallets will have to be designed and about 2000 fabricated for oversize fuels.

Assembly Costs

Capital Costs

Based on the above equipment modifications and additions required to produce oversize fuels, capital cost estimates for converting the fuel manufacturing facility to produce the quantities and sizes of fuel elements outlined in the assumptions for this study are as follows:

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ESTIMATED CAPITAL COSTS FOR CONVERTING ALSI PRODUCT FACILITY

TO OVERSIZE FUELS FOR C AND OLD REACTORS

	Estimated Cost	
	Case I*	Case II**
Equipment and Building Modifications	\$565,000	\$1,499,000
Project Overhead	175,000	501,000
Total Estimated Cost	\$750,000	\$2,000,000

* Oversize Fuels for Only C Reactor

** Oversize Fuels for C and Old Reactors

Essentially no additional capital expense will be incurred if the K Reactors are overbored. Provision for the extension of facility modifications to manufacture oversize fuels for other reactors accounts for about \$300,000 of the total estimate for Case I. Only Case II will require modification to existing building and utilities. These changes will be confined for the larger part to the canning and autoclave areas.

Operating Costs

A comparison of the estimated costs for manufacturing self-supported standard and oversize I & E fuel elements is shown below:

COMPARISON OF ESTIMATED FPD OPERATING COSTS

FOR SELF-SUPPORTED STANDARD AND OVERSIZE I & E FUELS

Fuel Dim. & Wt.	Standard 8" I&E*	Oversize 8" I&E*	Standard 6" I&E**	Oversize 6" I&E**	Oversize 8" I&E***
OD (Inches)	1.464	1.991	1.458	1.991	1.991
ID (Inches)	0.375	0.339	0.375	0.339	0.339
Length (Inches)	8.965	8.865	6.640	6.540	8.865
Wt. U (Lbs.)	7.320	14.970	5.290	10.820	14.970
Est. Fuel Mfg. Cost (100% Yield)					
Process Material	\$1.82	\$2.00	\$1.85	\$2.03	\$2.00
Operating Labor	0.47	0.70	0.47	0.70	0.70
Overhead	1.94	3.64	1.94	3.64	3.64
Conversion Cost/Pc.	\$4.23	\$6.34	\$4.26	\$6.37	\$6.34
Depreciation	\$0.40	\$0.75	\$0.40	\$0.75	\$0.75
Total Cost/Pc.	\$4.63	\$7.09	\$4.66	\$7.12	\$7.09
Total Cost/Lb.	\$0.63	\$0.47	\$0.88	\$0.65	\$0.47

* Natural Uranium

** 0.94% Enriched

*** Uniformly Enriched to 0.82%

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It will be noted that the above comparison of standard and estimated oversize I & E fuel costs is based on a 100% finished fuel yield, which can be readily converted to actual or estimated yield levels. Present I & E fuel element yields are in the order of 86%. Oversize I & E fuel yields should ultimately approach present present yields, even though preliminary yields may be as low as 50-60%. Incremental costs (labor and material) are expected to be about 15% higher for oversize than standard I & E fuel, even though the weight of oversize fuel will be twice that of standard I & E fuel. Necessary allowances have been made in the cost estimates for the attachment of projections. The welding of projections to standard I & E fuels will cost about \$0.26 per piece vs. an estimated \$0.32 per piece for oversize fuels.

POTENTIAL ALTERNATE PROCESSES

Since the ability of AlSi bonded fuel elements to withstand projected increases in reactor power and exposure has not been fully established, potential alternate processes have been conceived to achieve solid-state diffusion bonding of aluminum cladding to electro-nickel plated uranium cores, which includes hot-press, gas or fluid pressure bonding, extrusion cladding, and die casting. Only the gas pressure bonding and hot-press processes have been adequately developed to merit consideration as potential alternates for the existing lead-dip process at this time.

The technology for preparing aluminum alloy clad, solid-state nickel diffusion bonded fuels by the hot-press process is the most advanced. Although HAPO experience with this process has been limited to laboratory scale development and testing, production quantities (10,000-50,000/mo.) of hot-pressed Mark VII (I & E) fuel elements manufactured by Sylcor have been irradiated in the Savannah River reactors since early in CY 1957. Comparative experience in these reactors with SRP triple-dip (AlSi bonded) canned fuel elements has shown triple-dip material is at least four time more rupture prone than Sylcor hot-pressed fuel. Because of the observed improvement in performance, SRP has installed hot-press facilities in order to realize complete conversion to solid-state nickel diffusion bonded fuels. Feasibility of the gas pressure bonding process has been demonstrated by three sites,⁹ the Savannah River Laboratory, Atomics International, and Battelle.

HAPO irradiation experience with solid-state diffusion bonded I & E fuel elements has been limited essentially to 4 tubes charged alternately with HAPO hot-press and lead-dip canned fuel elements, which were exposed to 800 MWD/T in 1957. No significant difference was observed in the behavior of the fuel elements prepared by the two processes.

Based on Savannah River experience, it is postulated that solid-state diffusion nickel-bonded fuel elements should perform as well and probably better than AlSi

9 HW-65759, "Proposed Solid State Diffusion Bonding (SSDB) Process - Gas Pressure Bonding". E. A. Weakley. June 22, 1960. (Secret)

bonded fuel in the existing reactors, particularly at higher power and exposure. In order to expand HAP0 technology on potentially improved processes, a program has been initiated to obtain up to 2000 each of SRL gas pressure bonded and Sylcor and HAP0 hot-press I & E (CVN) fuel elements for a rigorous ex-reactor evaluation, followed by in-reactor testing. Arrangements for the procurement and preparation of these fuel elements is being expedited to permit completion of the ex-reactor evaluation by July 1961, and preliminary in-reactor testing by January 1962.

A brief descriptions of the hot-press and gas pressure bonding processes, including the apparent advantages of each are outlined below:

Hot-Press Process

The hot-press process, as developed at HAP0 and adopted by Sylcor to manufacture fuel elements for Savannah River, utilizes hydraulic presses equipped with resistance heated dies to apply the pressure (~ 12 tsi) and temperature (~ 600 C) required to produce a solid-state diffusion bond between electro-nickel plated uranium cores and prepared aluminum components. Major differences between the HAP0 and Sylcor processes are in the techniques used to electro-nickel plate the uranium cores; and pre-sizing of the fuel assembly prior to hot-pressing is excluded from the Sylcor process. Significant advantages of the hot-press process over the lead-dip process are as follows:

1. The finished fuel element aluminum cladding thickness can be controlled within more precise limits, since there is no dissolution or penetration of the cladding by the bonding media.
2. Larger diameter uranium cores may be used to offset the thickness (10 to 20 mils) of the braze layer in lead-dip canned fuel elements. The larger cores will increase reactor conversion ratios about 2%.
3. Nickel bond layers are stronger, tougher, and more uniform than AlSi bond layers. SRP reports an average bond strength of 17,000 psi for hot-press fuel elements; as compared to an average of 13,000 psi for HAP0 lead-dip fuel elements.
4. Nickel bonds are more resistant to corrosive attack in the event cooling water penetrates the aluminum cladding during irradiation.

Recognized or possible disadvantages of the hot-press process are:

1. In order to assure a sound, continuous, thin electro-deposited nickel plate on the cores to avoid uranium-aluminum diffusion, stringent standards must be applied to control uranium surface quality, surface hydrogen content, and surface preparation for plating.
2. Component cleanliness is as critical for hot-press as for the AlSi process to obtain an adequate bond between the cladding and bonding media.
3. Control of press alignment, die and mandrel tolerances, temperature gradients, pressures and holding times are all critical and essential to a uniform high quality product.

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Gas Pressure Bonding Process

The gas pressure bonding process differs from the hot-press process in that after the electro-nickel plate cores are assembled in prepared aluminum components, each assembly is evacuated by pre-sizing, the end closures are welded under vacuum, and the sealed assemblies are placed in an autoclave under gas pressure (5000-6000 psi) and temperature (460-525 C) to obtain a solid-state nickel diffusion bond. Inherent advantages of this process over the hot-press die method are as follows:

1. Uniform application of heat and pressure to all fuel element cladding surfaces.
2. The process is readily adopted to any fuel shape.
3. The process is self testing for any leaks in the fuel element cladding. Blisters will form on the cladding surface if there is a leak.
4. Bonding is accomplished without core deformation, which is typical of the hot-press die method.

Capital Cost Estimates

Based on the apparent advantages of gas pressure bonding over the hot-press process, a pilot plant facility for gas pressure bonding was included in the FY 1961 budget for an estimated total cost of \$480,000. It is proposed that this facility be installed in 306 Building with a small addition to house the required high pressure autoclave equipment. Funds were requested on a schedule to permit completion of the project work by the second quarter of CY 1962. As previously stated, preliminary out-of-reactor and in-reactor testing of SRL gas pressure bonded I & E fuels is scheduled for completion by January 1962.

High spot capital cost estimates for the conversion of the 313 Building fuel manufacturing facilities to the gas pressure bonding and hot-press processes are shown below:

ESTIMATED CAPITAL COSTS

FOR CONVERTING EXISTING FUEL MANUFACTURING FACILITIES

TO THE GAS PRESSURE BONDING OR HOT-PRESS PROCESS

	Process	
	<u>Gas Pressure Bonding</u>	<u>Hot Press</u>
Equipment and Building Modifications	\$3,265,000	\$3,155,000
Project Overhead	<u>1,630,000</u>	<u>1,580,000</u>
Total Estimated Cost	\$4,895,000	\$4,735,000

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The above estimates are based on the oversize fuel requirements outlined in the basic assumptions for this study, adapting existing AlSi product equipment where feasible to produce solid-state nickel diffusion bonded fuel elements by either of the two processes. Total design and construction time to achieve full conversion to the gas pressure bonding or hot-press process is estimated to be about 2 years. Since a decision to replace the existing AlSi process is contingent on the results of a fuel evaluation and testing program scheduled for completion by the end of CY 1961, alternate process facilities, if justified and authorized, could not be installed in sufficient time to produce the initial reactor loadings of oversize fuel elements.

ASSESSMENT OF RUPTURE POTENTIAL

Predictions relative to the irradiation performance of oversize AlSi bonded fuel must be based almost entirely on experience with present and I & E fuel designs. According to the reactor operating conditions assumed for this study, estimated maximum specific powers, and maximum core and surface temperature under which oversize I & E fuels in the C and old reactors will be expected to operate, as compared to current conditions for I & E fuels, are shown below:

Reactor	Max. Specific Power (KW/ft.)		Max. Uranium Temp. (°C)		Max. Cladding Surface Temp. (°C)	
	Current I & E	Oversize I & E	Current I & E	Oversize I & E	Current I & E	Oversize I & E
C	66	105	270	360	132	135
Old	67	110	300	395	137	140

Split Failures

Because of the increased wall thickness of the proposed oversize I & E uranium cores, thermal stresses in the cores during irradiation may ultimately reach a level where cleavage failures could occur. Studies¹⁰ have shown the thermal stresses in oversize fuel will fall between those for the present I & E fuel geometry and those at which cleavage failures were sustained in the solid fuel geometry. A cleavage threshold was reached for the existing solid fuel geometry at a specific power of about 40 KW/ft. and thermal stresses approximating 90,000 to 100,000 psi. Stresses of this magnitude may be experienced in oversize fuels of the proposed geometry operating in the range of 95 KW/ft. If cleavage failures constitute a limiting factor, the proposed oversize fuel design may be altered to minimize this problem. Increasing the core ID appears to offer the simplest means of minimizing thermal stresses in the uranium. If reactor physics

10 HW-67173, "C Reactor Overbore Study - Interim Report". W. L. Bunch. November 7, 1960. (Secret)

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or other requirements dictate against increasing the core ID of the oversize fuel element, alternate fuel geometries such as the rod-in-tube configuration could be considered.

There is some evidence that metallic uranium behaves like a viscous fluid rather than as an elastic metal in a neutron flux field, causing any thermal stresses in the uranium to be reduced to a relatively low level. Rates of change in neutron flux during reactor operation or rapid quenching during reactor shutdown, however, may lead to micro-cracking of the uranium core as a result of inadequate stress relief. Some micro-cracks have been observed in present I & E fuel geometries following irradiation. Although these micro-cracks have not contributed to cleavage failures, conditions that might cause propagation or growth of the micro-cracks would ultimately result in cleavage failures. Even though cleavage failures cannot be precisely predicted for oversize fuels, it is evident that this fuel will be operating closer to the cleavage threshold than current I & E fuel designs.

Hot Spot Failures

Since the extended surface of oversize I & E fuels will result in external surface temperature a few degrees lower than present I & E fuel designs, the potential for localized accelerated jacket corrosion (hot spot) ruptures should not change appreciably. Hot spot ruptures, which currently account for over 50% of the I & E fuel failures, are primarily attributed to fuel misalignment, eccentric positioning and warp during irradiation. Preliminary in-reactor tests indicate problems associated with centering and aligning fuel elements in reactor process tubes can be minimized through the attachment of projection rails to the surface of finished fuel elements for charging into either ribbed or ribless process tubes. Programs are also in progress to improve the irradiation stability of uranium, which will be equally applicable to oversize fuels. Based on limited run-to-rupture test data, projection I & E enriched fuels have demonstrated a 40-fold improvement in rupture resistance over control fuels operating at specific powers of 100 KW/ft. and exposures up to 960 MWD/T. Although sufficient irradiation experience has not been gained to predict the reduction in jacket corrosion ruptures that will result from projection fuels, it appears a 5 to 10-fold reduction can be expected.

Side Other and Internal Failures

Internal and side other ruptures in present I & E fuels are generally attributed to fuel quality oriented problems. All of the internal ruptures examined to date have been associated with coolant entry through the end closures, and it is suspected that many of the side other failures result from similar types of defects. Process improvements in progress to improve aluminum component wetting, reduce braze porosity, and improve weld integrity should alleviate these ruptures. These advances in fuel technology will also be equally applicable to the preparation of oversize fuels. An offsetting characteristic of the oversize fuel element is the residence time in the reactor, which will be about double the

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present residence time. Previous performance of fuel elements irradiated for 9 months indicated that minute weld defects coupled with braze porosity became evident as ruptures after about 9 months irradiation. It is estimated that side other and internal failures will be reduced by a factor of 2 to 3 over the present rate to give a potential rupture rate of 5 to 10 per million pieces discharged.

General

Of perhaps equal or greater concern in achieving the ultimate performance of oversize fuels is the ability of the AlSi braze to withstand anticipated future reactor operating conditions. Under current reactor operating conditions, AlSi bonded I & E fuels have shown evidence of bond deterioration following irradiation. In order to probe further the limitations of AlSi bonded fuels, a production test has been designed and is in progress to assemble both natural and enriched I & E fuel elements for irradiation at specific powers up to 130 KW/ft., and exposures up to 1600 MWD/T for subsequent examination. This test will incorporate all established fuels processing improvements which will enhance the characteristics of the AlSi bond with respect to strength, toughness, and freedom from porosity. Completion of the test is scheduled by the end of CY 1961.

Based on all the above considerations, it is estimated that the failure rate for the oversize fuel elements will be no worse than present I & E fuels irradiated under comparable conditions. The current failure rate is approximately 60/million for regular I & E production.

DEVELOPMENT EFFORT REQUIRED TO SUPPORT OVERSIZE FUEL PRODUCTION

Development effort at both the feed sites and at HAPO will be required to produce an optimum quality oversize fuel element. At the feed sites, development will be required to establish the proper relationship between billet diameter and rolling mill passes to obtain a 100% recrystallized grain structure, or to develop the extrusion parameters. Optimum heat treating parameters need to be established for the larger diameter core. Some tooling design and development will be required to machine and finish the pieces. The additional enriched uranium required will place additional burdens on the scrap recovery and recycle steps at the feed sites and will aggravate the need for the development of improved recovery processes for scrap.

In the fuel assembly process development will be required to optimize the canning cycle to produce strong bonds and non-porous braze layers in the oversize fuel elements. Optimum core-can and core-spire annuli must be determined. The additional weight of the piece will require changes in the operating sequences and techniques. Equipment design and development will be required to handle and process the oversize pieces. In the table below, the development effort required

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to support the fabrication of AlSi canned oversize fuel elements is listed for the various cases of reactor overboring. Should it be necessary to develop an extended surface fuel element or utilize an alternate process, development effort will be at least doubled.

	Man Years*		
	<u>Case 1</u>	<u>Case 2</u>	<u>Case 3&4</u>
	<u>C Reactor</u>	<u>C Reactor</u> <u>& 5 Old</u>	<u>All</u>
Feed Sites	2	3	3
Fuel Assembly	<u>3</u>	<u>5</u>	<u>6</u>
Total	5	8	9

* One man year of development effort is estimated to cost about \$50,000 and includes indirect charges, supporting services, and material.

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FLOW SHEET
LEAD-DIP PROCESS

Figure 1

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