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**ECONOMIC ANALYSIS OF
REPLACEMENT CORES FOR
SM AND PM TYPE REACTORS**

ALCO PRODUCTS, INC.

NUCLEAR POWER ENGINEERING DEPARTMENT
P. O. BOX 414, SCHENECTADY 1, N. Y.

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**ECONOMIC ANALYSIS OF
REPLACEMENT CORES FOR
SM AND PM TYPE REACTORS**

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Issued: October 5, 1961

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ABSTRACT

An economic analysis is presented for the fabrication of replacement cores for SM and PM type reactors, including analysis of various core types and core fabrication technologies. The analysis indicates that major savings are possible by utilizing Type 3 cores (40-mil plates, 25 w/o UO_2 , welded assembly) in all SM and PM type reactors, and that significant savings are possible by multiple core procurement and reprocessing, and relaxation of cobalt and tantalum requirements in Type 347 stainless steel.

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ECONOMIC ANALYSIS OF REPLACEMENT CORES FOR SM AND PM TYPE REACTORS

1.0 SUMMARY

A cost survey was conducted for development of replacement cores of the latest proven type for SM and PM type reactors. Major cost reduction is possible by using Type 3 cores (40 mil fuel plates, 25 w/o UO_2 , welded assembly) in all such reactors currently using Types 1 or 2. Other significant savings are possible by multiple core reprocessing, relaxation of cobalt and tantalum limits in Type 347 stainless steel, and multiple core procurement. Minor savings may be realized by quantity procurement of UO_2 and special Type 347 stainless steel.

2.0 INTRODUCTION

To the present, SM and PM type reactor cores have been procured on an individual basis, or at most, on a two core basis. This has been necessary because of the lack of an immediate need for the production of multiple cores. From an economic standpoint, it now appears desirable to procure several cores at one time. An economic survey was therefore made to determine the monetary savings that would be made by:

1. Selecting the latest proven core and using it in all SM and PM reactor systems.
2. Quantity procurement of the core materials
3. Multiple core procurement
4. Multiple core reprocessing

Costs stated herein were obtained during April-May, 1961. While these costs may change appreciably, the relationship of various costs remains reasonably constant. Therefore, the economic comparisons made continue to be valid.

This work was performed by Alco Products, Inc. under Task 3.6 of the Army Pressurized Water Reactor Support and Development Program, per AP Note 286.

3.0 DISCUSSION

3.1 Selection of Core Type

At the present time, there are four basic types of SM and PM fuel elements:

	<u>CORE TYPE</u>			
	<u>1</u>	<u>2</u>	<u>3</u>	<u>5</u>
Fuel Plate Thickness (in.)	0.030	0.030	0.040	0.070
Fuel	Geneva UO_2	Spherical UO_2	Spherical UO_2	Spherical UO_2 or UN
Fuel Loading	26 w/o	26 w/o	25 w/o	38 w/o UO_2 or 34 w/o UN
Poison	B_4C	B_4C	ZrB_2	Not Determined
Cladding	304 L	347	347	347
Assembly Method	Brazed	Brazed	Welded	Welded

Type 1 elements are currently in use in SM-1 Core I, (now spent), SM-1 Core II, PM-2A Core I and SM-1A Core I. Type 2 elements are being fabricated for SM-1A Core II. PM-2 Core II is also being fabricated; however, Geneva oxide is being used in place of spherical UO_2 . Type 3 was originally developed for SM-2 Core I, while Type 5 is an advanced core. All cores through Type 3 are proven, either in SM reactors or in irradiation programs on small size fuel plate specimens or both. Type 5 is untested, but Type 4, similar except only 0.040 in. thick, is currently in test on a small scale in ETR capsules. Results have not yet been received.

Studies have been made of Type 3 cores for use in the SM-1, SM-1A, and PM-2A. ⁽¹⁾ It appears feasible from a nuclear and thermal standpoint to use this type in all three reactors.

Prior to selection of either Type 2 or Type 3 for new cores, the relative advantages should be reviewed. The advantages in using Type 2 cores are:

1. Proven irradiation stability, since Type 2 is very similar to Type 1 which has been successfully irradiated as high as an estimated 60 a/o U-235 burnup in SM-1.
2. Proven core fabricating costs (approximately \$155,000 for a 45-element core, exclusive of absorbers and liaison charges).
3. Availability of at least two qualified vendors.

Type 3 cores have the following advantages for use as replacement Core III's:

1. Higher U-235 loadings. As an example, a Type 3 core in SM-1 will result in doubled core life, reducing the power cost.
2. Irradiation stability proven up to 55 a/o U-235 burnup on small size specimens⁽⁵⁾. While full size irradiation experience is not available, all indications point to the conclusion that the Type 3 fuel plates are more resistant to failure than Type 2. Fuel stringering and boride reactions, both believed to be detrimental, have been minimized.
3. The vendors for Type 2 cores should be able to produce satisfactory components. Some additional equipment, mainly in connection with vacuum sintering and element welding, will be required.
4. Core fabricating costs are estimated to be roughly equal to Type 2.

Process changes between Types 2 and 3 tend to offset each other. The increased cost of vacuum sintering should be balanced by the reduced cost of welded element assembly.

There may be a general increase in fabricating cost, since the tendency to "buy in" is decreasing. This, of course, would apply to either type.

The biggest saving, and the dominant consideration, results from energy output or life available with Type 3 cores. Latest nuclear calculations indicate that the SM-1 core life using Type 3 will double the current Type 2. (16 to 34 MWYR). Due to increased core life, the tangible saving would be \$155,000 for fuel element fabrication and \$20,000 for fabrication liaison. Intangible savings, difficult to estimate accurately, include increased plant safety by elimination of one refueling, decreased downtime for core changes, lower reprocessing costs if both types are reprocessed separately, halving of fuel shipping charges for both unirradiated and irradiated elements, and elimination of one complete core ZPE. The total saving, including these intangibles, would be \$200,000 to \$250,000. Absorber fabrication has not been included in the economic analysis, because the limited quantity of absorbers (7 per core) prevents appreciable savings even through multiple procurement.

Comparable savings are also possible with Type 3 cores in SM-1A and PM-2A. The apparent long term economic advantage is so high that Type 3 can be recommended for immediate future SM-1, SM-1A and PM-2A cores, even though initial fabrication cost could be slightly higher and irradiation experience is currently limited to small size specimens.

3.2 Fabrication Costs

The use of welding⁽²⁾ to replace brazing as the method of fuel element assembly in Type 3 should save a minimum of \$22,500 per core. Listed below is an estimate of costs, exclusive of items common to both techniques, which allows determination of savings:

	<u>Brazed</u>	<u>Welded</u>
Assembly	\$ 60.00	\$15.00
Welding machine or furnace	450.00	50.00
Machine operator changes	60.00	37.50
Atmosphere costs	75.00	nil
Spacer removal	-	7.50
Special inspection	-	7.50
Total	<u>\$645.00</u>	<u>\$117.50</u>
Differential		\$527.50

All charges were based on \$7.50/man hour. Assuming a conservative saving of \$500/per element, a 45 element Type 3 core would represent a \$22,500 cost reduction.

A basic disadvantage of brazed fuel elements, aside from their inherently poor corrosion resistance, is that an element rejected subsequent to brazing is a total loss. Assuming a conservative figure of \$75/per fuel plate fabricating cost, a rejected brazed stationary fuel element represents the following cost:

18	fuel plates, @ \$75/plate	\$1,350
2	side plates @ \$20/plate	40
	Reprocessing of UO ₂ to UF ₆ @ \$1.25/gram	650
	Total	<u>\$2,040</u>

On the other hand, welded fuel elements that are rejected may be salvaged by cutting through the side plates adjacent to the fuel plates with a milling cutter. After the edges have been cleaned, they may again be welded. Cost for unusable components and for this salvage operation is:

2 side plates @ \$20/plate	\$ 40
Machining	400
Total	<hr/> \$ 440

This represents a saving of \$1,600 per rejected element.

The brazed fuel element rejection rate, based upon experience with two vendors, has been about 10 percent, or 5 fuel elements for a 45-element core. Also experience with dummy and depleted elements indicates that welded element rejection rate would be less than 10 percent; therefore, a saving of (5 x \$1,600), or roughly \$8,000 could be realized. Combining the saving resulting from use of welding results in an overall saving of at least \$30,000.

Two areas add to the Type 3 core cost. Instead of hydrogen sintering of fuel cores as used in Types 1 and 2, the process employs vacuum sintering. A vendor would probably write off a considerable portion of the vacuum furnace cost, estimated at up to \$20,000, on the first order. The inclusion of Eu_2O_3 dispersion flux suppressors in the stationary fuel plates, as well as in control rod plates as done previously, adds some cost. Because flux suppressor fabrication tooling would have to be procured for the control rod fuel elements in any event, there should be little additional tooling charge. Roughly \$2,000 additional would be required for the materials, and the total, labor and materials, should be no more than \$4000, or \$5 per stationary fuel plate.

It may be concluded that the first Type 3 core would be very slightly cheaper than Type 2, and that subsequent Type 3 cores would be roughly \$25,000 less expensive. In actual procurement, however, this may not be readily evident, since, as reported previously the "buying in" phase of core fabrication is apparently over. Nevertheless, even at equal cost per core, the net result of replacing Type 2 with Type 3 cores is two core lives for the price of one.

3.3 Materials Procurement

The economics of core material procurement in quantity have been determined.

Each Type 3 core uses approximately 5000 pounds of Type 347 stainless steel. Present specifications⁽³⁾ call for 0.025 percent cobalt maximum and

0.01 percent tantalum maximum. With these limits, and with the knowledge that a 10-ton heat will give roughly 12,000 pounds of useable material, a graph may be constructed of cost/per pound vs. quantity procured (see Fig. 1). To effect any saving, two heats, or nearly enough material for five cores, would have to be procured at one time. This would save 11 percent. Reduction in cost for 3 heats, (7 cores) is an additional 4 percent while for 4 heats (9 cores) 1-1/2 percent more would be saved. The fifth heat (12 cores) would save an additional 1 percent. If material of this impurity level is required, a minimum order of two heats is indicated, with three heats being somewhat more desirable provided the material can be used up before storage charges reduce the saving realized. Beyond the third heat, it does not appear economically feasible, since funds will be tied up in material for a long period of time, and storage charges may well offset any saving.

It will also be noted on Fig. 1 that two other lines are plotted; normal price of Type 347 stainless steel and Type 347 with 0.05 percent maximum cobalt and 0.1 percent maximum tantalum. For a nominal price increase, roughly \$0.10/per pound, Type 347 that may be used in reactor cores can be procured. Preliminary studies⁽⁴⁾ of relaxed impurity limits at Alco reveal that 0.05 percent maximum cobalt and 0.1 percent maximum tantalum will not add appreciably to the activity buildup problem. Apparently the primary system activity is influenced to a great extent by the impurities in the remainder of the system, such as the steam generator's stainless steel tubes. If the core material impurity limits are relaxed, the balance of the primary system stainless steel impurity limits would be tightened to the same specifications for replacement items such as the steam generator. The combination of the two is expected to eventually reduce the overall activity level. This relaxation is highly desirable, since material costs per core would be reduced up to \$12,000 and there would be no necessity for procurement of large quantities at one time.

It is also conceivable that the core stainless steel impurity limits could be relaxed without making compensating changes in other parts of the primary system. Further work on this concept is therefore indicated.

Early investigations of spherical UO_2 costs indicated that procurement of sufficient fuel for three to five cores would reduce cost roughly 10 percent. The latest quotation from a qualified vendor indicates, however, that savings would be nil. This vendor is now quoting on a license basis a price of \$475/per Kg of UO_2 , regardless of quantity, with an additional fixed charge of \$2,000 for startup and cleanup of the process for each order. Multiple procurement would prorate the fixed charge over more Kg of fuel and would be a small reduction from single core materials procurement.

At the present time, no other areas of saving by multiple material procurement are foreseen.

FIGURE 1

PRICE FOR TYPE 347 STAINLESS STEEL
(AVERAGE OF PLATE & SHEET PRICE VS. QUANTITY PROCURED)

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3.4 Core Procurement

Some savings are possible through multiple core procurement. While direct comparison of bids on various reactor cores is difficult due to differing requirements, materials supplied, bidders, etc., a comparison may be made on the bids for SM-1A and PM-2A Core II. Neither core was a complete unit; that is, the number of elements was incomplete or a full set of absorbers was not included. Bids were obtained on each core separately, and both together. The saving that could be realized by procuring both cores at the same time was an average of 5-1/2 percent (average for the three low bidders). If both had been complete cores, the saving might have been 1 to 2 percent higher. This saving is basically caused by elimination of process qualification for one of the cores. If four or five cores were procured at one time, a fabricator could probably assign personnel to the job for a prolonged period of time, and, by such efficient utilization of manpower, cut cost for the cores by roughly 10 percent over the one core cost. This saving would be approximately \$15,000 per core.

3.5 Reprocessing

Reprocessing of cores is also an area where savings may be realized. Reprocessing plant capacity is approximately 40 Kg of U-235/per day, at a rate of \$15,300/per day. Also, a minimum of three to a maximum of eight days is added to the charge for startup, shutdown and cleanup. This additional time equals the processing time if processing time is between the three to eight day limit. Therefore, cost would be as shown on Table 1.

Type 3 cores are more economical than Types 1 or 2 to reprocess, since it takes fewer cores to reach a reasonable economic level. The table indicates that spent cores should be stored until sufficient have been required for economical reprocessing; the spent core storage facilities and charges would, of course, have an influence on the number of cores stored.

4.0 RESULTS AND CONCLUSIONS

The cost analysis of replacement cores for SM and PM type reactors reveals three modes of saving. Cost reduction is possible by using Type 3 cores in all reactors. Significant savings, but of much less magnitude, are possible by multiple core reprocessing, relaxation of cobalt and tantalum limits in Type 347 stainless steel, and multiple core procurement. Minor savings may be realized by quantity procurement of UO₂ and quantity procurement of special Type 347 stainless steel.

These costs are tabulated in Table 2 for a 45 element core, based on prices

TABLE 1
CORE REPROCESSING COSTS

Core Type 1 or 2 (~ 15 KG U-235/Core)				Core Type 3 (~ 21 Kg U-235/Core)			
<u>No. of Cores</u>	<u>Total</u>	<u>Cost/Core</u>	<u>Cost/Kg</u>	<u>No. of Cores</u>	<u>Total</u>	<u>Cost/Core</u>	<u>Cost/Kg</u>
One	\$61,200	\$61,200	\$410	One	\$61,200	\$61,200	\$292
Two	61,200	30,600	205	Two	61,200	30,600	146
Three	65,500	25,500	170	Three	76,500	76,500	122
Four	76,500	19,125	128	Four	76,500	19,125	91
Five	76,500	15,300	102	Five	91,800	18,560	88
Six	91,800	15,300	102	Six	91,800	15,300	73
Seven	91,800	13,114	88	Seven	122,400	17,485	83
Eight	91,800	11,475	76	Eight	122,400	15,300	73

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TABLE 2
CORE COSTS BY TYPE AND SINGLE
Vs. MULTIPLE PROCUREMENT

Item of Cost	Type 1 & 2 Cores		Type 3 Cores		Type 3 Cores	
	One Core	Four Cores	One Core	Four Cores	One Core	Four Cores
UF ₆ to UO ₂	15, 000	54, 000	23, 500	86, 000	23, 500	86, 000
Low impurity 347	-	-	-	-	15, 000	60, 000
Relaxed impurity 347	5, 000	20, 000	5, 000	20, 000	-	-
Core fabrication *	175, 000	590, 000	175, 000	590, 000	175, 000	590, 000
Core reprocessing	61, 200	76, 500	61, 200	76, 500	61, 200	76, 500
Total	\$256, 200	\$740, 500	\$264, 700	\$772, 500	\$274, 700	\$812, 500
Available MWYR**	16	64	34	136	34	136
\$/MWYR	\$16, 000	\$11, 600	\$ 7, 800	\$ 5, 700	\$ 8, 100	\$ 5, 950

* Includes liaison

** Approximate, in SM-1 or SM-1A

available in May 1961.*

The saving possible by selection of Type 3 cores as replacements in SM and PM reactors is large when compared with other savings. Even the most uneconomical approach to Type 3 (one-core procurement, low impurity S.S.) offers a saving of 50 percent/MWYR, while on a four core, relaxed impurity S.S. basis, the Type 3 core offers a reduction in cost per MWYR of better than 60 percent, over the one Type 2 core cost, or roughly \$10,000/MWYR.

Procurement of stainless steel and UO₂ materials in quantity results in only small economic saving. However, an appreciable saving is possible in procurement of low impurity Type 347 stainless steel if the tolerances are relaxed somewhat.

It is recommended that further work be done on the Type 347 stainless steel impurity level vs. system activity problem. While the cost reduction possible through relaxation of impurity limits is relatively small, it is still appreciable. A saving of \$50,000 per 20 year reactor life is completely possible.

It is also recommended that the cost of core reprocessing be closely monitored during SM-1 Core I reprocessing. Since the reprocessing costs given herein are estimates only, it would be highly desirable to arrive at actual monetary figures.

* Since core costs change rapidly, these figures are representative only. Relative costs, however, would remain nearly the same, making the data valid for estimation purposes.

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