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ORNL
CENTRAL FILES NUMBER

58 - 7 - 86

DATE: July 24, 1958
SUBJECT: Effect on Power Cost of Substituting Aluminum For Zirconium
Fuel Cladding in a Boiling Water Reactor
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COPY NO. 27

Abstract

The substitution of Al-clad for Zr-clad fuel necessitates reducing the operating temperature. The amount of saving that must be made in fabrication and chemical reprocessing to overcome the cost of operating at reduced thermal efficiency is estimated for a boiling water reactor.

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EFFECT ON POWER COST OF SUBSTITUTING ALUMINUM FOR ZIRCONIUM FUEL CLADDING IN A BOILING WATER REACTOR

1.0 INTRODUCTION

A study of the effect of plant thermal efficiency on nuclear power cost is reported in ORNL-CF-58-7-85. That study provides a basis for the present one, in which the cost of substituting aluminum for zirconium as a fuel element cladding material is considered.

Alloyed zirconium, with its low thermal neutron capture cross section, good resistance to corrosion, and fair mechanical properties, is a good fuel cladding material. It is a costly material, however, and is expensive to fabricate. It also is difficult to handle in chemical reprocessing. Aluminum has roughly the same cross section as zirconium, but has somewhat lower corrosion resistance and poorer mechanical properties at reactor operating temperatures. Its principal merits are its low cost and its ease of fabrication and processing.

Work at Argonne National Laboratory² indicates that addition of 1% nickel to 1100 aluminum greatly improves its resistance to corrosion in water. The corrosion resistance and high temperature strength of aluminum can probably be improved by further developments in alloying. Nonetheless, it is likely that a reactor in which the clad is aluminum would have to operate at a lower temperature than one in which the clad is zirconium. The purpose of the study reported here is to see whether aluminum alloy cladding might be competitive at reduced reactor operating temperatures.

If aluminum-clad fuel is to compete with zirconium-clad fuel, the increase in power cost due to reduced thermal efficiency must be offset by a saving in fabrication and chemical processing costs. To obtain an idea as to the magnitude of the required savings, a comparison has been made using as a basis a large boiling water reactor station operating at various steam temperatures below its regular operating temperature. A boiling water reactor was selected because the temperature difference between steam and fuel clad is lowest in this type of reactor system. This favors the use of aluminum. The station chosen for the comparison is the Dresden Nuclear Power Station which is to use zircaloy-2 as the clad. This station will have a net electrical output of 180,000 kw.

2.0 SUMMARY

The use of aluminum alloy clad fuel elements in the Dresden reactor would require that the operating temperature be reduced by some unknown amount. To offset the increased costs that this would entail, the savings in fuel fabrication and chemical reprocessing costs shown in Table 2-1 would have to be realized.

These figures are based on an fuel irradiation level of 11,000 Mwd/metric ton. At lower burnups, the required savings would be proportionately larger.

Table 2-1

Required Savings in Fabrication and Reprocessing Costs to Balance
Decreased Cost of Operation at Reduced Thermal Efficiency

<u>Steam Temperature, °F</u>	<u>Net Thermal Efficiency, %</u>	<u>Required Savings, \$/kg U</u>
541 (Design)	28.8	-
516	26.9	17
491	26.0	27
466	25.0	38
441	24.1	50
391	22.0	75

Savings of \$27/kg U seem readily attainable with aluminum. With such a saving, the Dresden Station could be operated with a steam temperature of about 490°F, which might permit the use of aluminum alloy as the clad.

In all likelihood, the cost of fabricating and reprocessing zirconium clad fuels will drop in the future, and the potential savings with aluminum would disappear. Meanwhile, however, it is believed that development work on high-temperature aluminum alloys is warranted.

3.0 EFFECT ON POWER COST OF OPERATING DRESDEN STATION
AT REDUCED THERMAL EFFICIENCY

Data on the design characteristics and performance of the Dresden Station, are given in Table 3-1.

The maximum temperature to which the aluminum alloy clad can be subjected is not known. For this reason, comparisons are made at steam temperatures 25, 50, 75, 100, and 150°F below the steam temperature for the Dresden Station. The factors affected by these reduced steam temperatures are shown in Table 3-2.

Table 3-1

Data^a on Dresden Nuclear Power Station

Reactor type	Dual cycle boiling water
Reactor heat output, kw	624,200
Net electrical output, kw	180,000
Net thermal efficiency, %	28.8
Coolant temp., °F	546
Reactor press., psia	1015
Steam temp., °F	541
Steam press., psia	970
Fuel	UO ₂ pellets with Zircaloy-2 jacket, 1.5% U-235 enrichment
Fuel loading, kg U	54,500
Expected irradiation, Mwd/metric ton	11,000
Total U throughput, kg/yr	14,500
Plant load factor, %	70

a. Data from "Atomic Energy Facts"¹ and from General Electric's "Progress Report on Dresden Station".³ Where the two sources differ, data from the GE report are used.

Table 3-2

Factors Affected by Reduced Steam Temperature

	Dresden Station	Steam Temperature Difference, °F				
		25	50	75	100	150
Steam temp., °F	541	516	491	466	441	391
Reactor press., psia	1,015	820	657	520	406	236
Net thermal eff., % ^a	28.8	26.9	26.0	25.0	24.1	22.0
Reactor heat output, kw ^b	624,200	669,000	692,000	720,000	747,000	818,000
Fuel loading, kg U	54,500	58,300	60,200	62,600	65,000	71,100

a. Determined as 0.6 x Carnot cycle efficiency, using T₂ = 540°F.

b. For net electrical output of 180,000 kw.

For purposes of comparison, the following assumptions are made concerning cost factors of the Dresden Station:

- (a) Turbine plant cost = \$100/net kw electricity
- (b) Reactor plant cost = \$200/net kw electricity
- (c) Operating and maintenance costs = 1 mill/kwh_e
- (d) Plutonium credit = \$12/gram metal
- (e) Out-of-pile inventory = 7.25 tons U = 1/2 annual throughput
- (f) Sum of spent fuel storage and shipping costs = \$10/kg U
- (g) Sum of costs of converting UNH to UF₆ and UF₆ to UO₂ = \$15/kg U
- (h) Plant write-off rate = 15%/yr
- (i) Fuel inventory charge = 4%/yr

It should be noted that these figures do not represent attempts to guess the actual figures for the Dresden station.

In Table 2-3, power cost items other than fuel fabrication and chemical reprocessing are shown for the reference station and for the reduced-steam-temperature stations. The differences in the totals of these cost items represent the amounts that must be saved in fabrication and chemical reprocessing. The required savings are shown also in terms of \$/kg U.

Table 5-3

Power Cost Items Other Than Fabrication and Reprocessing

	Dresden Station	Cost, mills/kwh _e				
		Steam	Temperature	Difference, °F		
		25	50	75	100	150
Turbine plant	2.45	2.46	2.46	2.47	2.48	2.52
Reactor plant	4.89	5.03	5.11	5.22	5.35	5.65
In-pile inventory	0.29	0.31	0.32	0.33	0.34	0.38
Operating and maintenance	1.00	1.00	1.00	1.00	1.00	1.00
Burnup, incl. Pu credit	0.96	1.02	1.06	1.10	1.14	1.25
Conversions, storage, shipping	0.33	0.34	0.36	0.37	0.38	0.40
Out-of-pile inventory	0.04	0.04	0.05	0.05	0.05	0.05
Total of above items	9.96	10.20	10.36	10.54	10.74	11.25
Excess over Dresden cost	-	0.24	0.40	0.58	0.78	1.29
Excess, expressed as \$/kg U	-	17	27	38	50	75

A saving of \$27/kg U in fabrication and reprocessing costs appears to be readily attainable. The Dresden reactor will contain about 8360 kg of zirconium, or 0.346 kg/kg U. With Zr sponge at \$4.00/lb (expected price when production rate is 1.5 million pounds/yr), seamless tubing will cost \$48/lb.⁵ Thus, the Zr tubing alone will cost nearly \$17/kg U if the yield from tubing to finished element were 100%, which is unlikely. Inasmuch as Mallory, Sharon Metals is fabricating 44 miles of Zr tubing for the Dresden reactor,⁶ and the reactor will contain 30 miles, it may be concluded that the yield is more like 70%. This would bring the Zr tubing cost to \$24/kg U. On another basis, Herron, et al,⁴ estimated that the zirconium cost for the Dresden reactor at \$64/kg U. Aluminum alloy tubing, at the same yield, would cost less than \$1/kg U at a recently quoted price of \$0.20/ft. It is safe to assume that the cost of producing finished elements and of reprocessing irradiated elements would be considerably more than \$4/kg U greater for Zr than Al clad material. Thus, there should be no difficulty in saving at least \$27/kg U with aluminum clad.

The foregoing has been based on the assumption that aluminum clad fuel could be irradiated to the same burnup as zirconium clad fuel. Should the life of the aluminum clad fuel be shorter, the required savings would be larger than those shown in Table 5-3. The differences in neutron absorption cross section and mechanical strength between Al and Zr have been neglected. It is estimated, however, that the conversion ratio would be only about 2 per cent lower for the Al clad fuel.

In view of the uncertainty as to the temperature to which aluminum cladding can be carried, it cannot be stated that a Dresden-type reactor with aluminum clad fuel would be competitive with one having zirconium clad fuel. If an aluminum alloy that had adequate creep strength at about 590°F (310°C) were available, it might well be competitive.

It is believed that in addition to the development work on zirconium alloys, a parallel effort on high-temperature aluminum alloys is warranted.

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