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3.

POWER COST ASSOCIATED WITH USE OF N^{15} IN BREEDER REACTORS

Introduction

In thorium breeder reactors, the problems associated with maintaining a uniform concentration of ThO_2 in a ThO_2 - D_2O slurry could be eliminated if a useable, soluble thorium compound were available. The only thorium compound which has the desired solubility in D_2O and a sufficiently low neutron-absorption cross-section appears to be $Th(N^{15}O_3)_4$. However, nitrate compounds are unstable when exposed to reactor conditions, and the N^{15} required to make up nitrate losses is relatively expensive. This combination of circumstances could lead to undesirably high power costs in reactors containing thorium as $Th(N^{15}O_3)_4$. The study here evaluates the cost of power associated with the decomposition of thorium nitrate in a thorium breeder reactor, based on presently available decomposition and cost data.

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Summary

The use of N^{15} in the blanket region of a thorium breeder reactor does not appear economically attractive. Based on a two-region reactor in which 5% of the total power is generated (as fission power) within a blanket containing 1000 gm Th/liter, the power cost associated with nitrate decomposition would be about 140 mills/kw-hr, if N^{15} cost \$1/gm. If a nitrate synthesis plant were near the reactor, the cost of $HN^{15}O_3$ from this plant might be about \$3/pound; under this circumstance, the power cost associated with nitrate decomposition would be about 4 mills/kw-hr. If losses of N^{15} in the synthesis process were 1%, and the replacement nitrogen cost \$1/gm, the additional associated power cost would be about 1.4 mills/kw-hr. If the blanket contained 500 gm Th/l, the power costs due to $Th(NO_3)_4$ decomposition would be about 2/3 those for a solution containing 1000 gm Th/l. If all fuel were continuously removed from the blanket region by blanket-processing, the rate of nitrate decomposition would be appreciably lower due to the lower G_{N_2} value associated with γ -ray exposure relative to that associated with fission exposure. Under this circumstance, the nitrate decomposition cost would be about 5 mills/kw-hr if N^{15} cost \$1/gm, and about 0.5 mill/kw-hr if N^{15} cost \$0.10/gm. However, removal of fuel immediately after formation would be economically undesirable because of the associated chemical processing costs.

Cost of N^{15}

The cost of N^{15} has been estimated¹ to be \$1 to \$5/gm for large-scale production of nitrogen containing 99-99.9% N^{15} . In the study here the lower figure of \$1/gm has been used for make-up N^{15} .

The nitrogen leaving the reactor system (as a result of nitrate decomposition) should not be very radioactive after scrubbing and a relatively short holdup time (N^{15} has a low neutron-absorption cross-section, and N^{16} has a half life of about 7 seconds), and so could be used to synthesize $HN^{15}O_3$. Reagent grade fuming HNO_3 is presently priced at \$3/pound,⁽²⁾ while commercial CP nitric acid (~60% acid) is \$0.15/pound.⁽²⁾ Because of the purity requirements in a breeder reactor (particularly with respect to hydrogen), and the relatively small nitric acid production rate associated with a reactor-synthesis plant, it is doubtful if the synthesis plant could synthesize thorium nitrate for less than \$0.03/gm N^{15} (equivalent to \$3/pound HNO_3). [A 2000 Mw (thermal) power station with 5% of this energy generated in $Th(NO_3)_4$ solution would require an equivalent $HN^{15}O_3$ synthesis rate of no more than 8 tons/day, compared with 55 tons (100% HNO_3)/day produced by typical commercial units⁽³⁾ (as 60% acid)].

Reactor-Decomposition of Nitrates

The rate of decomposition of $Th(NO_3)_4$ upon exposure to reactor radiation has been measured by Boyle and Mahlman.⁽⁴⁾ Their results are given in Table I in terms of G, the molecules of N_2 produced per 100 ev absorbed energy. From the data given in Table I, it is seen that the G_{N_2} associated with γ -radiation alone is about 1/10 that associated with fission-radiation.

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TABLE I

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NITRATE DECOMPOSITION RATE AS A FUNCTION OF NITRATE CONCENTRATION

Solution	Th Molality m	Approx. Th Conc. gm Th/liter	G $\left(\frac{\text{molecules N}_2}{100 \text{ ev}} \right)$		K $\equiv$ G/m γ -, n-, fission radiation
			γ -, n-radiation	γ -, n-, fission-radiation	
$\text{Th}(\text{NO}_3)_4 - \text{H}_2\text{O}$	0.55	130	0.003	0.016	0.029
$\text{Th}(\text{NO}_3)_4 - \text{H}_2\text{O}$	1.5	300	0.005	0.047	0.031
$\text{Th}(\text{NO}_3)_4 - \text{H}_2\text{O}$	2.7	550	0.006	0.063	0.023
$\text{Th}(\text{NO}_3)_4 \cdot 3\text{Be}(\text{NO}_3)_2 - \text{H}_2\text{O}$	7.0	1300		0.16	0.023

$\left[\begin{array}{l} 0.015 \text{ if} \\ \text{consider} \\ 2 \text{ Be}(\text{NO}_3)_2 \end{array} \right] \approx$
 $\text{Th}(\text{NO}_3)_4$

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Power Cost Associated with N^{15} Replacement

If G , the decomposition rate of nitrogen, is written as

$$G_{N_2} = K m \quad (1)$$

where K = proportionality constant

m = molality of Th in $Th(NO_3)_4$ solution

the rate of N_2^{15} formation exposed to a fission power density of 10 kw/l would be

$$\begin{aligned} 6.25 \times 10^{22} \left(\frac{\text{ev}}{\text{l-sec}} \right) \times K m \left(\frac{\text{molecules } N_2}{100 \text{ ev}} \right) \times \frac{30}{6 \times 10^{23}} \left(\frac{\text{gms } N_2^{15}}{\text{molecules } N_2^{15}} \right) \\ = 3.12 \times 10^{-2} K m \left(\frac{\text{gms } N_2^{15} \text{ formed}}{\text{l-sec}} \right) \end{aligned} \quad (2)$$

Since a mole of $Th(N^{15}O_3)_4$ contains 4 moles of N^{15} , a Th molality of m would contain

$$4m \times 15 \frac{\text{gms } N^{15}}{\text{kg } D_2O} \approx 60 \frac{\text{gms } N^{15}}{\text{l}} \quad (3)$$

Thus, the time, τ , required to decompose an amount of nitrate equal to that originally present (at constant nitrate concentration) would be

$$\tau = \frac{60 m}{3.12 \times 10^{-2} K m} \text{ sec} \approx \frac{2 \times 10^3}{K} \text{ seconds} \approx \frac{0.56}{K} \text{ hrs.} \quad (4)$$

At 10 kw/l and a thermal efficiency of 25%, on the average one liter would produce in τ days

$$\frac{10(0.25)}{\tau} \times \frac{0.56}{K} = \frac{1.4}{K} \frac{\text{kw hrs elec.}}{\text{l}} \quad (5)$$

If the solution contained $N^{02} \frac{\text{gm Th}}{\text{liter}}$ $\left[\text{as Th } \left(N^{15}O_3 \right)_4 \right]$ and it cost $\frac{C \text{ dollars}}{\text{gm } N^{15}}$ to replace the decomposed nitrogen, the cost, C_B , associated with nitrate decomposition would be

$$C_B = \frac{K N^{02} \left(\frac{60}{232} \right) C \times 10^3}{1.4} \frac{\text{mills}}{\text{kw-hr}} \quad (6)$$

based on power generated within the nitrate solution. Combining the information in Table I with Eq. 6, we obtain the cost of nitrate decomposition given in Table II.

TABLE II

COST OF NITRATE DECOMPOSITION, BASED ON
POWER GENERATED WITHIN NITRATE SOLUTION

Th Conc., gms/liter	250	500	1000
<u>Case</u>			
a $\left\{ \begin{array}{l} K = \frac{G}{M} \text{ (see Table I)} \\ C = \$1/\text{gm} \\ C_B = \text{mills/kw-hr} \end{array} \right.$	0.03 1390	0.023 2130	0.015 2770
b $\left\{ \begin{array}{l} K \\ C = \$1/\text{gm} \\ C_B = \text{mills/kw-hr} \end{array} \right.$	0.003 139	0.0023 213	0.0015 277
c $\left\{ \begin{array}{l} K \\ C = 0.03 \$/\text{gm} \\ C_B = \text{mills/kw-hr} \end{array} \right.$	0.03 42	0.023 64	0.015 83

No values are given for C_B corresponding to the lower values of K , since the lower nitrate decomposition rate would result in lower synthesis-demand rates, which would probably cause the effective cost of N^{15} to be much $> \$0.03/\text{gm}$.

Based on fission power in the nitrate solution, the time required to decompose an amount of nitrate equal to the original concentration would be given by Eq. 4; these times are given in Table III.

TABLE III

TIME REQUIRED TO DECOMPOSE ALL OF ORIGINAL NITRATE CONCENTRATION,
BASED ON 10 KW/LITER FISSION POWER IN NITRATE SOLUTION

Th Conc. gms/l	Time Required for Complete Decomposition hours
250	18.4
500	24
1000	37

Because of the large number of cycles associated with replacing dissociated nitrate with synthesized nitrate over a year's operation time, the nitrate losses may become significant. Assuming fission power is generated within the nitrate solution, 1% loss of nitrate per cycle, and that this loss is made up at a cost of $\$1/\text{gm } N^{15}$, the cost associated with nitrate losses would be 1% of the costs given in Table II, Case a. The total cost of nitrate decomposition based on fission power generated within nitrate solution, assuming that the cost of synthesized nitrate were $\$0.03/\text{gm } N^{15}$ and that 1% of the decomposed nitrate were replaced at $\$1/\text{gm } N^{15}$, would be 56, 85,

and 111 mills/kw-hr for solutions containing 250, 500, and 1000 gm Th/liter, respectively (rather than the values given in Table II, case c).

If 5% of the total energy generated were dissipated within the nitrate solution, the effective cost of nitrate decomposition based on total power would be that given in Table IV.

TABLE IV

EFFECTIVE COST OF NITRATE DECOMPOSITION IF 5% OF TOTAL ENERGY GENERATED IS DEPOSITED WITHIN NITRATE SOLUTION, BASED ON TOTAL POWER.

Th Conc. gm/liter		250	500	1000
Case (See Table II)				
a)	C_B mills/kw-hr	69	106	138
b)	C_B mills/kw-hr	6.9	10.6	13.8
c)	C_B mills/kw-hr	2.1	3.2	4.1
d)	K	0.03	0.023	0.015
C = \$0.03/gm for synthesized material; C = \$1/gm for nitrate losses, which are considered to be 1% of decomposed nitrate.				
	C_B mills/kw-hr	2.8	4.2	5.5
e)	K	0.003	0.0023	0.0015
C = \$0.03/gm N ¹⁵				
	C_B mills/kw-hr	0.21	0.32	0.41

DISCUSSION

The use of N^{15} as $\text{Th}(\text{NO}_3)_4$ in the blanket region of a two-region reactor does not appear economically attractive if appreciable fission power is generated within the nitrate solution, due to the high decomposition rate of nitrates, and the relatively high cost of N^{15} . If only gamma-heating occurs within the blanket region, the picture is more encouraging because of the lower nitrate decomposition rate; however, a low blanket-fission-power implies a fast blanket-processing-cycle-time, which is economically undesirable. Neglecting the latter effect, use of nitrates in a γ -field would still necessitate N^{15} costs appreciably less than \$1/gm (perhaps about \$0.03/gm), which would probably require the development of synthesis plants to re-synthesize the decomposed nitrates. If only γ -heating occurred within the nitrate solution (blanket region), less than 5% of the total energy generated would be deposited in a blanket solution containing 1000 gm Th/liter (perhaps 3% would be deposited); also, decreasing the nitrate concentration would decrease the percentage energy deposited. If breeding is important, however, it would be necessary to have Th concentration of 500 gm Th/liter or greater, and so the blanket heat generation due to γ -heating would probably be 2-3 kw/liter. Thus, the value of C_B given in Table IV, Cases b and e, may be too high by a factor of 2. Such a reduction would also lower the throughput requirements of a synthesis plant, resulting in higher unit cost for N^{15} .

It is doubtful whether the effective cost of N^{15} (including inventory charges and chemical processing charge due to fast blanket-cycle-time) can be lower than about 2 mills/kw-hr even under optimistic conditions.

1. Hayford, Johnson, Levin, Shacter, Von Halle, Feasibility of Large Scale N¹⁵ Production for Nuclear Reactors, Report K-1232, August 1955.
2. Chemical and Engineering News, "Quarterly Report on Prices --- Second Quarter 1956," June 25, 1956.
3. E. R. Riegel, Industrial Chemistry, Reinhold Publishing Corp., New York (1949).
4. J. W. Boyle and H. A. Mahlman, HRP Quarterly Progress Report, January 31, 1955, ORNL 1853, p. 201.
Ibid HRP Quarterly Progress Report July 31, 1956, ORNL 2148, p. 139.