**Coal-Fired Alkali Metal
Power System Design Study
Technical Progress Report for Period
October 1, 1976-December 31, 1976**

Garland Samuels

OAK RIDGE NATIONAL LABORATORY

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COAL-FIRED ALKALI METAL
POWER SYSTEM DESIGN STUDY

TECHNICAL PROGRESS REPORT FOR PERIOD
October 1, 1976 — December 31, 1976

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COAL-FIRED ALKALI METAL POWER SYSTEM DESIGN STUDY
FIRST QUARTERLY
TECHNICAL PROGRESS REPORT FOR PERIOD
October 1, 1976 — December 31, 1976

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ABSTRACT

This report is the first of a series of quarterly progress reports for the Coal-Fired Alkali Metal Power System Design Study. The primary effort during this period was the compilation of physical and thermodynamic properties of potassium and cesium, the analysis of a series of potassium and cesium turbine designs and the determination of the cycle efficiency for both fluids for a variety of operating conditions.

Scope of the Design Study

The objective of the Coal-Fired Alkali Metal Power System Design Study is to establish a reference design for a 200 MW(e) alkali metal vapor/steam Rankin cycle system employing a coal-fired fluidized bed furnace and to prepare a detailed preliminary design of a fluidized bed furnace. This will be accomplished by preparing designs for both potassium and cesium vapor cycle systems and making a comparison of these designs. The results will be analyzed and potassium or cesium will be chosen as the cycle fluid and one of the designs will be selected as the reference system. The reference system will be used for the preparation of a detailed preliminary design of a fluidized bed furnace-boiler.

The program will consist of two phases. The first phase will compare several systems using both potassium and cesium as the working fluid. The scope of work for this phase of the program will include the following major tasks:

1. Parametric cycle analyses for cesium and potassium power systems.
2. Furnace-boiler conceptual designs for furnace pressures of 1 to 10 atm.

3. Condenser-steam generator conceptual designs for cesium and potassium at several condenser temperatures.
4. Metal vapor turbine design and analysis.
5. Survey of cesium availability and cost.
6. Conceptual designs and layouts of selected systems.

The results of these tasks will provide a variety of conceptual designs for both cesium and potassium. A detailed comparison will be made of the relative merits of the various concepts from which a reference design using either potassium or cesium will be selected. This system will be used to prepare a detailed preliminary design of a fluidized bed furnace-boiler.

Technical Progress

Work on this design study was started this quarter. The initial effort was concentrated on compiling physical properties data on cesium and potassium, analysis of the high temperature alkali metal topping cycle, analysis of the metal vapor turbine and designs of various header and manifold arrangements for the boiler.

The compilation of physical and thermodynamic properties of cesium and potassium was completed. The basic thermodynamic data used were those published by Ewing, et al., in NRL Reports 6233 and 6246. However, these data do not cover the lower temperatures needed for our current work, and it was necessary to prepare computer codes to extend the range to lower temperatures of interest. Mollier diagrams were prepared for the temperature range of 1050°R (583°K) to 2300°R (1278°K) for cesium and from 1200°R (667°K) to 2300°F (1278°K) for potassium. The wet region for both diagrams extends down to 28% moisture. Tables of the specific heat, viscosity, and thermal conductivity for both the liquid and vapor, and a table of the sonic velocity were prepared for both working fluids. A draft report documenting the data sources and calculational procedures was completed.

Most of the metal vapor turbine design work was completed. This task is limited to analyses to determine the number of stages, blade height and stress, and the turbine efficiency. The comparison of the turbine designs and efficiencies for cesium and potassium are based on the decision to make the units nearly identical in size and number of stages. It is possible to take advantage of the smaller enthalpy change across the turbine for cesium to reduce the number of stages as compared to potassium. Although this would result in a somewhat less expensive cesium unit it would also reduce the efficiency of the unit by several points. Rather than take this approach, the speed of the cesium unit was made one-half that of the potassium unit which gives machines of nearly the same size and number of stages. This lower speed has a very significant effect on the materials requirements for the blades and disks and is discussed later.

In analyzing the turbines for the various cycle conditions it was assumed that the only difference in the turbine efficiency for the various cases was that associated with supersaturation, moisture, and exhaust losses. The mixture losses were assumed to be 0.6 percent for each percent of moisture and the exhaust loss was assumed to be the kinetic energy in the fluid from the last stage. The supersaturation losses were calculated as a function of the enthalpy drop per stage and were found to range between 2% for a stage enthalpy change of 11 Btu/lb (25.6×10^3 J/kg) to 4% from an enthalpy drop of 15 Btu/lb (34.9×10^3 J/kg) for cesium. Comparable results for potassium are a loss of 2% for a stage enthalpy drop of 35 Btu/lb (81.4×10^3 J/kg) and 4% for an enthalpy drop of 60 Btu/lb (140×10^3 J/kg). These results are based on the assumption that the return to equilibrium occurs along a constant pressure line which is probably somewhat conservative.

In carrying out both the turbine and the cycle analyses, it was assumed that vapor, for regenerative feed heating, would be bled from the turbine between all stages except the first and second. Furthermore it was assumed that moisture removal devices were located at each bleed point. The efficiency of the moisture removal was taken as 25%, i.e., 25% of the moisture in the working fluid at each bleed point is

removed with the bleed flow. This value is well within the 20 to 35% efficiency demonstrated on a small potassium turbine tested by General Electric for the space power program.

Both the turbine and cycle analyses were carried out at turbine inlet temperatures from 1850°R (1028°K) to 2000°R (1111°K) and condenser temperatures from 1350°R (750°K) to 1550°R (861°K). The number of turbine stages varies from 3 to 5 and the number of feed heaters used in the system was always 2 less than the number of turbine stages. The feed pump energy requirements were based on a pump efficiency of 70% and a head equal to twice the difference between the boiler and condenser pressures. No allowances were made for mechanical and electrical losses in the turbine and generator. The results of the analyses are summarized in Tables 1 and 2. The efficiency of the alkali metal cycles varied from 13% to 26% or from 77% to 80% of the Carnot efficiency. The turbine efficiency varied between 77% and 82%. These turbine efficiencies were calculated by subtracting the sum of the supersaturation losses, moisture losses and exhaust losses from a basic machine efficiency of 88%.

Table 2 gives information on the turbine design used in the analysis. For all cases the turbine hub radius was fixed at 20 in. (0.51 m). The most interesting column is that showing the height of the first stage blade for a power output of 2 MW for the stage. The blade heights are the same for a cesium unit operating at 1800 rpm as for a potassium unit operating at 3600 rpm. This means that the centrifugal stress on the first stage rotor blade, which is proportional to the square of the speed, is four times as great for the potassium turbine as for the cesium unit. Furthermore, as can be seen from Table 1, the required flow area and thus the blade height increases much more rapidly for the potassium unit than for the cesium unit with the last stage requiring about 1.5 times the area. As the centrifugal blade stress is directly proportional to the rotor annulus area, the centrifugal blade stress in the last stage rotor will be about six times greater for the potassium turbine.

These differences in stress have a significant effect on the blade and rotor creep rates and allowable operating temperatures. The relation between creep rate, stress and temperature is shown in the following equation.

$$\epsilon = A\sigma^m e^{-h/kT}$$

where

- ϵ = creep rate
- A = constant
- σ = stress
- m = constant
- h = activation energy
- k = Boltzmann's constant
- T = absolute temperature

The value of m is in the range of 4 to 8 while the value of the activation energy is normally between 80,000 and 100,000 for materials of interest. For illustration purposes a value of m = 6 and h = 80,000 will be used. For these values, the creep rate for the first stage blades in the potassium unit is 4100 times that for the cesium unit. If one were to try to offset this higher creep rate with a lower temperature, then the blade temperature would have to be reduced from about 1850°R (1028°K) to 1550°R (861°K). However as the temperature is reduced, the flow area and thus the blade height would increase and the required temperature reduction would be even greater.

For the cesium turbine the centrifugal stress at the root of the first stage blade is about 1200 psi (8.3×10^6 Pa) for each MW of power output for a blade with a constant cross sectional area. A tapered blade would reduce this stress by about one-third.

The design effort on the furnace-boilers is still in the early conceptual stage. The units envisioned for furnace pressures of 3 to 10 atm (0.3 to 1.0 M Pa) have a fluidized bed about 20 ft in diameter. The boiler will consist of vertical tubes arranged into bundles or modules. The modular concept is used for headering purposes and also to facilitate assembly of the units and for maintenance and repair if

necessary. The tubes, which will probably be Incoloy 800, are 1.0 in. (2.54 cm) OD and are located on 2 in. (5.08 cm) centers throughout the furnace.

Data to be used in other parts of the system have been selected for the overall plant analysis. The steam pressure for the bottoming system will be about 2000 psi (1.4×10^7 Pa). The overall efficiency that will be used for the steam system will be 42, 40.5 and 39% for steam temperatures of 1000°F (811°K), 900°F (756°K) and 800°F (700°K) respectively.

The coal to be used will be Illinois No. 6, the same as for the ECAS study and the combustion air system will be designed for 15% excess air. Stack gas losses will be based on a stack temperature of 300°F (422°K).

Table 1. Summary of Alkali Metal Cycle Analysis

Turbine Inlet Temperature °R	Condenser Temperature °R	No. of Turbine Stages	No. of Feed Heaters	Cycle Efficiency %	% of Carnot Efficiency	Ratio of Turbine Exit Area to Inlet Area	Turbine Efficiency %
<u>Cesium</u>							
2000	1350	5	3	25.4	78.1	21.6	78.8
2000	1450	4	2	21.3	77.6	11.1	78.6
2000	1550	4	2	17.2	76.6	6.2	80.7
1900	1350	5	3	22.9	79.1	15.5	79.2
1900	1450	4	2	18.4	77.8	8.0	79.7
1900	1550	3	1	14.2	77.2	4.6	78.8
1850	1350	4	2	21.6	79.9	13.3	77.9
1850	1450	4	2	17.8	82.3	6.7	80.4
1850	1550	3	1	13.0	80.1	3.7	81.9
<u>Potassium</u>							
2000	1350	5	3	25.3	77.8	38.9	77.3
2000	1450	5	3	21.8	79.2	17.4	79.0
2000	1550	4	2	17.7	78.6	8.8	78.9
1900	1350	5	3	22.8	78.9	26.3	78.7
1900	1450	4	2	18.5	78.1	11.9	78.6
1900	1550	4	2	14.7	80.0	6.2	80.6
1850	1350	5	3	21.6	79.8	21.3	79.0
1850	1450	4	2	17.3	79.9	9.7	79.5
1850	1550	3	1	12.9	79.7	4.9	79.9

Table 2. Summary of Turbine Design Analysis

Working Fluid	Turbine Inlet Temperature °R	Condenser Temperature °R	Turbine Hub Radius in.	Turbine Speed rpm	First Stage Blade Height For 2MW Output in.	Rotor Inlet Temperature °R	Inlet Nozzle Mach No.
Cs	2000	1350	20	1800	3.8	1855	.80
Cs	1900	1450	20	1800	5.5	1780	.77
Cs	1850	1550	20	1800	7.0	1750	.75
K	2000	1350	20	3600	3.8	1850	.86
K	1900	1450	20	3600	5.5	1780	.84
K	1850	1550	20	3600	7.0	1740	.83

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