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ORNL/TM-6406

**Potassium Vapor Topping Cycle
Technical Progress Report for Period
January 1, 1978-March 31, 1978**

Robert S. Holcomb

MASTER

OAK RIDGE NATIONAL LABORATORY
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POTASSIUM VAPOR TOPPING CYCLE

TECHNICAL PROGRESS REPORT FOR PERIOD
JANUARY 1, 1978 - MARCH 31, 1978

MASTER

Robert S. Holcomb

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ABSTRACT

The potassium vapor topping cycle is a concept for increasing the efficiency of the Rankine vapor cycle by raising the peak temperature by employing a potassium vapor cycle with a turbine inlet temperature of 1500 to 1600°F (815 to 870°C) in which the waste heat rejected from the condensing potassium vapor is transferred to boiling water and steam in a conventional steam cycle. An efficiency of about 50% is calculated for this cycle with a natural circulation potassium boiler fired by gas or oil.

A DOE program is underway at ORNL to build a full-scale potassium boiler tube bundle and burner module and test it with water and then potassium. This is the sixth in a series of quarterly progress reports.

The new liquid level indicator was installed, and operation was resumed in January. A total of 14 hr operation was obtained with steady boiling, and the performance tests were completed except the maximum power test. The results indicate excellent boiler performance with no problems of superheating in the boiler tubes. A potassium leak occurred at a tee in the liquid return line. A new tee has been installed and the system is nearly ready to begin endurance testing.

I. SCOPE

A. Introduction

An important step that can be taken to reduce our national fuel consumption is to increase the efficiency of our thermodynamic cycles. Few realize that a major factor in keeping our consumption from increasing more rapidly than it has during the past century has been an increase in the thermal efficiency of steam plants by about a factor of 8. Unfortunately, there has been no further increase since about 1950 because at that time we reached the upper practicable temperature limit for the steam cycle; namely, about 1000°F (538°C). To reach higher

thermal efficiencies it will be necessary to go to higher temperatures, and this in turn implies the use of other working fluids. A leading candidate for an advanced thermodynamic cycle is a potassium or cesium vapor cycle.

The approach proposed by ORNL entails raising the peak temperature of the thermodynamic cycle by employing a potassium vapor Rankine topping cycle that operates with a turbine inlet temperature of 1500 to 1600°F (815 to 870°C) and superimposed on a conventional steam cycle with a turbine inlet temperature of about 1000°F (538°C) by transferring the waste heat rejected from the condensing potassium vapor to the boiling water of the steam cycle.¹ Design studies have indicated that with a natural circulation boiler fired by gas or oil in a potassium topping cycle, a cycle efficiency of about 50% can be achieved.²

The basic layout of the power plant envisioned is shown in Fig. 1. Three basic systems are coupled to form the power plant, i.e., a gas turbine that supercharges the combustion chamber for the potassium boiler, the potassium vapor topping cycle, and an essentially standard steam cycle. The most important components involving new technology are the furnace-potassium boiler unit and the potassium condenser-steam generator unit, both of which employ tube bundle modules as their basic unit of construction.

The ORNL gas- or oil-fired potassium boiler concept employs a basic tube bundle module that consists of two annular rows of 1-in. (2.54 cm) diameter stainless steel tubes arranged around a 22-in. (56 cm) diameter, long, vertical, cylindrical chamber. A full-scale test unit is shown in Fig. 2. The flame from the burner directs hot gas upward through this combustion chamber. The tubes are bent at the top to provide flow passages between them so that the hot gas from the top of the combustion chamber can flow radially outward and then downward through an outer annulus over the outer row of tubes. To reduce the amount of heat transfer surface area required, the furnace and combustion chambers would be operated at a pressure of 6 to 10 atm, i.e., substantially above the 2 atm which would be the design operating pressure of the potassium vapor system. Potassium would circulate under natural

Fig. 2. Photo of the ORNL potassium boiler under construction.

thermal convection from a header tank at the top of the tube bundle through two downcomers, one on either side, to two ring-shaped manifolds at the bottom, and then vertically upward through the tubes back to a header drum and vapor separator at the top of the header tank.

Preliminary studies have also indicated that a particularly attractive system could be obtained by coupling a potassium or cesium vapor cycle to a fluidized bed coal combustion system. One very promising concept is a fluidized bed that would operate at a temperature of about 1700°F (927°C) and a pressure of about 5 atm. This pressure yields an acceptable pressure drop with a bed of sufficient depth to employ a vertical tube natural circulation boiler. To minimize the problems of turbine bucket erosion, corrosion, and deposits, the hot gases leaving the bed would be cooled to about 1000°F (538°C) before being admitted to a gas turbine to give a power output just sufficient to drive the compressor. The studies indicate that a cycle efficiency of about 48% can be achieved with this type of system.

The key factor in achieving the lower capital cost and higher thermal efficiency projected by the ORNL design lies in employing a vertical tube, natural circulation boiler rather than a horizontal tube, forced circulation boiler. Therefore, being a new design, it is very important that it be shown that the natural circulation boiler can be operated successfully. A program for testing a full-scale tube bundle and burner module first on water and then potassium was initiated to investigate the uncertainties that have become evident in the course of the design. These uncertainties fall into four major problem areas: burner performance, combustion gas heat transfer, flow distribution of the two-phase potassium liquid-vapor mixture and the tube bundle temperature distribution, and the vapor separator effectiveness. In many cases, the cumulative uncertainties in the analysis are substantial and can be resolved only by obtaining test data. A section through the test module is shown in Fig. 3.

The water test was designed to get as detailed an insight into these problems as possible. The water tests were run with boiling at atmospheric pressure. In the first phase of the tests, the top of the

Fig. 3. Section through the gas-fired potassium boiler tube bundle module, burner and furnace assembly.

boiler drum was open so that visual observation of the flow from the boiler tubes was possible. The boiler drum being open also made it much easier to install instrumentation to obtain a more detailed picture of the flow distribution than will be the case in the tests with potassium.

The potassium test will provide a test of the boiler bundle and furnace at the design conditions of full pressure and temperature for potassium operation. While visual observation and measurement of flows from each boiler tube cannot be done while operating with potassium, the tube bundle temperature distribution will provide an indication of the potassium two-phase flow distribution.

The results obtained from the test program will provide boiler design data that will be beneficial to both gas-fired and fluidized bed coal-fired systems.

B. Objective

The overall objectives of the program are to complete the water test; design, fabricate, and install the potassium system; and run the potassium test.

1. Water test

- a. Check out the boiler and furnace.
- b. Check out combustion air seals.
- c. Measure tube bundle and flue gas temperature distribution.
- d. Observe argon distribution.
- e. Operate at a power level of 2×10^6 Btu/hr.
- f. Observe boiling stability.
- g. Establish minimum power level for stable boiling in outer tube bank.
- h. Measure heat load on individual boiler tubes.
- i. Observe vapor separator performance.

2. Potassium system

- a. Complete the design of components and modifications for the potassium system.
- b. Perform system modifications and fabrication of components, including tower extension, condenser, drain tank, piping, sample box, electrical system, instruments and controls.
- c. Install the potassium system components.

3. Potassium test

- a. Check out system.
- b. Measure tube bundle and flue gas temperature distribution.
- c. Monitor boiling nucleation problem.
- d. Operate at power levels up to 4×10^6 Btu/hr.
- e. Observe liquid level control.
- f. Observe vapor separator performance.
- g. Run 2000 hr endurance test.
- h. Determine minimum argon flow required for nucleation.

II. PROGRESS TO DATE

A. Work Prior to FY 1977

Work on alkali metal vapor cycles at ORNL began with some design studies under the Aircraft Nuclear Propulsion program in 1954 and was resumed in 1958 with studies of nuclear electric space power plants. This led to an extensive series of component and system tests in the course of which ~200,000 hr of boiling potassium system operation were obtained in the early and middle 1960's. When the pressing need for reductions in both fuel consumption and heat rejection to the environment became evident in 1970, a design study of a potassium vapor cycle plant was carried out under NSF sponsorship.¹⁻³ This plant was designed to operate on clean gaseous fuel derived from coal, the preferred fuel-of-the-future for central stations at that time. The study showed that the greatest uncertainties from both the design and cost standpoints lay in the potassium boiler, and that these could be resolved best by designing, building, and testing a full-scale tube bundle and burner

module first with water and then potassium. Funds to begin this work were made available by NSF in July, 1972, and NSF funding was continued in 1973. When ERDA was proposed in June, 1973, the responsibility for the potassium vapor cycle work became uncertain, with NSF, the AEC, OCR, and NASA all having claims in this area. As a consequence of these uncertainties, the program remained unfunded through 1974 until ERDA was formed, at which time some interim funds were made available from NSF, and funds from ERDA-FE finally became available at ORNL for the program in December, 1975.

The shakedown and performance tests of the burner operating outside the boiler in the open air were completed in May, 1976. The water system installation was completed, and the water test was begun in July 1976. Detailed design of the potassium system was resumed in April, 1976, and much of the work was completed by the end of September. Fabrication of components for the potassium system such as the condenser and drain tank was initiated in August.

B. Accomplishments in FY 1977

The water test program was completed in March.^{4,5} The tests included measurement of the argon distribution, heat load of individual boiler tubes, boiler temperature distribution, combustion gas temperature distribution, combustion air pressure drop and vapor separator performance. Boiler preheating tests were run, and it was concluded that an external air preheater was needed for preheating the boiler before filling with potassium.

The design of the potassium test system was completed in June.⁶ An elevation drawing of the system is shown in Fig. 4. Installation of the major components for the potassium system and construction work on the equipment tower was completed in June. A photograph of the equipment tower after completion of construction is shown in Fig. 5. The piping and electrical wiring was installed during the last quarter of FY 1977, and the potassium system installation was completed in September.⁷ The checkout of the instruments and controls was nearly completed. The fill

ORNL-PHOTO 6708-77

Fig. 5. Equipment tower after completion of construction.

and drain tank was filled with potassium in preparation for initial filling of the boiler.

C. Progress During October-December, 1977

Operation of the boiler with potassium was initiated in October.⁸ The first three runs were for short periods without sustained boiling. Two operating problems were encountered in these runs: plugging of the argon nucleators after the boiler was drained and refilled, and plugging of small valves in the vent lines from the fill tank and from the condenser.

It was found that the argon flow could be reestablished by raising the system temperature and applying momentary high pressure to the nucleator line. The cooling of the vapor trap in the fill tank vent line was increased to prevent plugging in that line. A vapor trap employing a column of low temperature liquid potassium was installed in the condenser vent line to prevent plugging there.

A boiling run of about 50 min duration was then made with a burner power level of about 1.9×10^6 Btu/hr. During this run a small potassium leak occurred in the welding nozzle connecting the boiler liquid level indicator lead sheath to the potassium liquid return line. Attempts to repair the level indicator leads were unsuccessful, and it became necessary to install an alternate liquid level indicator. A level indicator which makes use of two argon bubbler tubes was chosen and was installed.

III. TECHNICAL PROGRESS

A. Summary of Progress This Quarter

Work was completed on the installation of the argon bubbler liquid level indicator, and operation was resumed in January.

A total operating time at steady boiling conditions of about 14 hr was completed. The performance tests were completed with the exception of the maximum power test. The performance data indicate the following: stable boiling appears to occur in the tubes in the outer row at power levels of 2.5×10^6 Btu/hr and above; the indicated temperatures of the

boiler tubes and the vapor separator agree well with the potassium saturation temperature corresponding to the indicated pressure; the boiler shroud temperature is less than 1500°F, thus reducing the possibility of creep buckling.

A potassium leak occurred at a weld on a 2-in. tee in the liquid return line. A crack was found in the weld that is believed to have been caused by thermal cycling as a result of the 600° temperature difference between the two liquid streams entering the tee.

A new tee was designed to provide for mixing of the two streams to avoid severe thermal cycling stresses. The tee has been fabricated and installed in the system. It is expected that the system will be ready for operation the first week of April to begin endurance testing.

B. Progress by Task

Work was completed on the modification and reinstallation of the secondary containment that had been removed for the installation of the argon bubbler liquid level indicator. The system was refilled with potassium, and operation was resumed on January 11.

1. System operation

The system was operated for about an hour and a half at power levels up to 3.6×10^6 Btu/hr. The potassium was then returned to the fill and drain tank and heated to about 1300°F to allow any oxygen present in the potassium to be removed by combining with the zirconium foil in the purification trap in the tank.

The boiler was refilled again and a performance test of about 1.5 hr was run. Plugging of the condenser argon vent line was again encountered. The system was shut down, and several modifications were made to the condenser venting system to try to eliminate plugging. The most significant change was to install electric heaters and insulation on the vent line from the condenser enclosure outlet to the inlet of the potassium bubbler trap to prevent freezing of any potassium that might be carried over in the argon.

Testing was again resumed on January 30. Performance data at power levels up to 1.9×10^6 Btu/hr were obtained during a run of about one hour. A run at a power level of 3.9×10^6 Btu/hr was begun, but the temperature at the top of the argon separator was inadvertently allowed to reach 600°F, and this led to the carryover of a quantity of potassium to the bubbler trap and caused it to fill up and then plug the vent line from the bubbler. The system was shut down, the potassium was melted in the vent line and bubbler, and the excess liquid was transferred from the bubbler to the drain tank.

The system was restarted, and about 3.5 hr of additional performance testing was completed without difficulty. A fairly complete set of performance data had been obtained, and the shakedown test was considered to have been completed at this point. A short occurred in an electric heater on the vent line causing it to fail, and this led to plugging. The boiler was shut down, and the heater was replaced and the vent line cleared.

Performance testing was resumed on February 7, and the system was operated for a period of about 4.5 hr during which repeat performance data were obtained for power levels up to 3.0×10^6 Btu/hr. A total operating time at steady boiling conditions of about 14 hr had been achieved at this point. A summary of the boiling test runs are given in Table 1. The performance tests have been completed with the exception of determining the maximum power at which the burner can be operated without exceeding the allowable limit for the pressure difference across the boiler shroud. While the boiler was running at about 3.0×10^6 Btu/hr, a potassium leak developed. This was first indicated by the smoke detector in the condenser enclosure exhaust duct. The system was shut down, and the potassium was drained to the drain tank. The drain tank level indicated a loss of 135 pounds of potassium.

The leak occurred at a weld on a 2-in. tee in the liquid return line where the reflux stream from the central vapor header of the condenser joins the condensate stream from the bottom of the argon separator. The reflux contained considerable liquid entrained from the boiler and was at about 1500°F. In order to prevent potassium carryover in the

Table 1. KVTC operating summary of boiling runs.

Date	Duration of run min	Burner power 10^6 Btu/hr	Mixed liquid temperature	Boiler pressure (downcomer), psig	Tube* temperature °F
11/7/77	120	2.4 max	-----TRANSIENT OPERATION-----		
1/11/78	30	2.5	1480	INSTRUMENT BLOCKED	1547 - 1567
	60	3.6	1480	INSTRUMENT BLOCKED	1563 - 1582
1/18/78	80	2.0	1500	14.0	1512 - 1533
1/30/78	25	1.0	1540	15.5	1523 - 1544
	10	1.7			1529 - 1550
	15	1.9			1530 - 1546
2/2/78	40	1.2	1420	6.0	1402 - 1434
	40	2.1	1460	11.0	1464 - 1494
	100	2.9	1470	12.0	1467 - 1499
	30	3.2	1480	16.0	1555 - 1588
2/7/78	75	1.2	1480	15.5	1460 - 1477
	75	2.4			1498 - 1518
	45	2.4			1497 - 1520
	70	3.0			1495 - 1520

*Upper, inner row.

argon vent line, the condenser had been operated with subcooling of the condensate, and the temperature of the liquid from the argon separator was about 900°F. A crack was found in the weld at the tee, and this is believed to have been caused by thermal cycling as a result of the 600° temperature difference between the two liquid streams entering the tee. A review of the inspection reports on the weld indicated that a good weld had been made, and no deviations from the quality assurance requirements were found.

A film of potassium oxide dust was found on lower portions of the condenser tubes and liquid lines. This film was easily removed by wiping, and the system has been cleaned. The cooling air provisions on the argon separator have been modified to provide increased cooling on the separator while holding a higher condenser temperature. A new tee was designed to provide for mixing of the two streams and avoid severe thermal cycling stresses. A photograph of the parts for the mixing tee are shown in Fig. 6. The tee has been fabricated and has been installed in the system, as shown in Figs. 7 and 8. New electric heaters, thermocouples and insulation have been installed on the liquid return piping.

Additional potassium was added to the fill tank. The entire contents of the tank were purified by hot-trapping at 1250°F for 100 hr. Preparations for refilling the system are underway. It is expected that the system will be ready for operation the first week of April.

2. Data analysis

Preliminary analysis has been done on the data from the performance test runs.

Comparisons of the mean temperature of the inner and outer tubes near the boiler drum at various power levels indicate that stable boiling appears to be starting in the outer tubes at about 2.5×10^6 Btu/hr. The temperature of the individual tubes in the outer rows tends to verify this.

The indicated temperature of the inner and outer tubes, as well as the vapor separator temperatures, agree well with the expected temperatures at various operating pressures. This indicates that no sustained superheating is occurring.

ORNL-PHOTO 6255-78

Fig. 6. Mixing tee for potassium liquid return line.

Fig. 7. View of mixing tee after installation in condenser.

Fig. 8. Second view of mixing tee after installation in condenser.

The boiler shroud temperatures were less than 1500°F at power levels up to 3.2×10^6 Btu/hr. This is considerably lower than the 1700°F anticipated. Thus the possibility of creep buckling is reduced, which will permit operation at higher power levels.

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