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**PATHFINDER ATOMIC POWER PLANT
DESIGN AND OPERATION OF A BOILING AND
SUPERHEATING HEAT TRANSFER LOOP**

August 15, 1963

MASTER

Submitted to
**U. S. ATOMIC ENERGY COMMISSION
NORTHERN STATES POWER COMPANY**
and
CENTRAL UTILITIES ATOMIC POWER ASSOCIATES

by

**ALLIS-CHALMERS MANUFACTURING COMPANY
ATOMIC ENERGY DIVISION
Milwaukee 1, Wisconsin**

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 AND SUPERHEATING HEAT TRANSFER LOOP

by
 R. B. Jerman and Mark Healy
 Submitted to

U. S. ATOMIC ENERGY COMMISSION
 NORTHERN STATES POWER COMPANY
 and
 CENTRAL UTILITIES ATOMIC POWER ASSOCIATES

by
 ALLIS-CHALMERS MANUFACTURING COMPANY

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Approved:

C. B. Graham
 C. B. Graham
 Manager
 Nuclear Power Dept.-Greendale

Approved:

Hibbert Hill
 Hibbert Hill
 Vice President -
 Engineering

ALLIS-CHALMERS MANUFACTURING COMPANY
 ATOMIC ENERGY DIVISION
 MILWAUKEE 1, WISCONSIN

NORTHERN STATES POWER COMPANY
 15 SOUTH FIFTH STREET
 MINNEAPOLIS 2, MINNESOTA

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FOREWORD

This report, "Design and Operation of a Boiling and Superheating Heat Transfer Loop", is one of a series of reports on research and development in connection with the design of the Pathfinder Atomic Power Plant.

The Pathfinder plant is located at a site near Sioux Falls, South Dakota, and is scheduled for operation in 1963. Owners and operators of the plant will be the Northern States Power Company of Minneapolis, Minnesota. Allis-Chalmers is performing the research, development, and design as well as being responsible for plant construction.

The U. S. Atomic Energy Commission, through Contract No. AT(11-1)-589 with Northern States Power Company, and Central Utilities Atomic Power Associates (CUAPA) are sponsors of the research and development program.

The plant's reactor will be of the controlled recirculation boiling reactor type with nuclear superheater.

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DESIGN AND OPERATION OF A BOILING AND SUPERHEATING HEAT TRANSFER LOOP

1.0 INTRODUCTION

One problem that faced designers of the Pathfinder Power Plant was the determination of the heat transfer and fluid flow characteristics of boiler and superheater fuel elements which operate at heat fluxes ranging from 70,000 to 500,000 Btu/hr-ft². In particular, the following information was needed:

1. Two-phase pressure drop and steam void distribution in the boiler elements.
2. Surface temperature and maximum allowable heat flux in the boiler and superheater elements.
3. Pressure drop in the superheater element.

To obtain this data a test loop was designed, fabricated, and is now in operation at the Greendale Laboratories.

2.0 OBJECTIVE

This report describes the design and operation of the boiling and superheating heat transfer loop at Greendale.

3.0 HEAT TRANSFER LOOP

3.1 Basic Design

The test loop (Figure 1) was designed to accommodate partial fuel element assemblies or a full scale boiler element and

Figure 1 ... Heat Transfer Loop Photo.

one superheater element. By varying the power output of the element and the flow conditions, any element of the core could be simulated.

Because one boiler element and one superheater element do not constitute a critical mass (that is, such an arrangement will not support a self-sustaining nuclear reaction), another means of generating heat had to be found. Several methods of heat generation were investigated, including: combustion of gases in the elements ... circulating externally heated liquid metals or gases through the elements ... and electrical resistance heating. Use of hot gases was eliminated because their low heat capacity made it practically impossible to get the required range of heat fluxes. Externally heated liquid metals were not feasible because of the safety hazard presented by having them in close proximity with the water. Electrical resistance heating had none of the above disadvantages, but did present minor problems of measuring temperatures in an electric field, and in designing the element so that its electrical resistance and the electrical power source characteristics were compatible for generating the required amount of heat. The above problems were minor, however, when compared to those associated with the other methods. Electric heating, therefore, was chosen as the means of heat generation in the elements.

Direct-current heating was selected since alternating-current causes temperature measurement errors in thermocouples due to induced emfs generated by the fluctuating magnetic field. An error may also be caused by an impressed emf when heating with d-c, but this was eliminated by using an ungrounded thermocouple.

Investigation of test element designs employing both high (greater than 75v) voltage, low current sources ... and low voltage, high current sources revealed that, in general, low voltage sources allowed simpler element design. For instance, in high voltage design of an aluminum, nickel, or stainless steel rod, a higher resistance or heating element must be placed in each rod and electrically isolated from it. This would have obviously made test element design very complex. In low voltage design the rod itself carries the current and the heat is generated in the rod walls. It appeared, therefore, that the best type of power supply was a low voltage, high current d-c source. Figure 2 shows a complete 81-pin boiler test element for a low voltage d-c source.

The low voltage characteristics at a required power range of 25 to 1800 kw eliminated conventional d-c generators. Hence, the choice was limited to rectifiers and unipolar generators. The decision to use unipolars was based on the advantages of smaller space requirements and greater ease of control. Later,

Figure 2 ... Complete 81-Pin Boiler Test Element.

because of its availability, a small conventional d-c generator was added to the loop as a power source for boiler single-pin and small sub-assembly tests.

The following considerations were used in determining the necessary size, flexibility, construction materials and general flow path of the loop:

1. Instrumentation and equipment had to be capable of testing fuel elements generating from 25 to 1800 kw of heat, with water flow rates from 15 to 600 gpm.
2. Boiler and superheater fuel elements had to be tested at pressures up to 1500 psi and temperatures up to 600 F and 1200 F respectively.
3. Both boiler and superheater fuel elements had to be tested at the same time.
4. Boiler fuel element tests had to be run using either natural or forced circulation of the coolant.
5. Loop water purity had to be maintained without a bypass demineralization system.
6. The water and steam flow paths had to duplicate reactor conditions.

3.2 General Flow Path

When a boiler fuel element test is being run, water is pumped vertically upward (Figure 3) through the simulated element where

Figure 3 ... Heat Transfer Loop Schematic. (43-024-777)

it is heated and a portion transformed to steam. Next, the two-phase mixture enters a vertical, gravity-type separator where the water and steam are separated. The water leaves the separator, enters a downcomer pipe and is recirculated through the test section. The steam is throttled by valve V_1 to about one-half of its upstream pressure, condensed, and then drained into a storage or receiver tank. A large reciprocating-type feed pump forces this water through a pre-heater and then back into the recirculating water flow. A small cooler just ahead of the feed pump prevents water from flashing into steam in the pump suction line.

When a superheater test is being conducted, the steam generated in the boiler test section is passed vertically downward through the simulated superheater fuel element where it is superheated. It is then throttled by valve V_2 , desuperheated (to protect the condenser), condensed, and returned to the storage tank. Cooling water for the desuperheater is obtained by bleeding part of the feed pump discharge through valve V_5 .

A small piston-type pump periodically injects make-up water into the system which replaces the water used to lubricate the feed pump packing and the main circulating pump seal.

An independent closed water loop consisting of a circulating pump, an air-cooled heat exchanger, and a sump tank cools the

pump lubricating systems, the main loop water entering the feed pump suction, and also the 10,000 amp electrical cables that supply power to the test sections.

3.3 Main Components

The ratings of the main loop components are presented in Table I. All parts of the equipment which come in contact with the loop water or steam are made of Type 304, 316 or 347 Stainless Steel. This was done to maintain water purity and eliminate the need for a by-pass demineralization system.

TABLE I
CHARACTERISTICS OF TEST LOOP COMPONENTS

<u>COMPONENT</u>	<u>RATING</u>	<u>NOTES</u>
Unipolar Generators (2)	60,000 amps, 30 volts each	Can be varied 0-30 volts. Each is controlled independently. Can be used in series or parallel.
Conventional D-C Gen. (2)	5,000 amps, 45 volts each	Can be varied 0-45 volts. Each is controlled independently. Can be used in series or parallel.
Large Recirculation Pump	600 gpm, 200 ft. head	1500 psi, 600 F operation
Small Recirculation Pump	75 gpm, 72 ft. head	1500 psi, 600 F operation
Feedwater Pump	5-25 gpm, 0-1500 psi head	Variable speed, reciprocating type
Make-Up Pump	5 gpm, 0-1500 psi head	Constant speed, reciprocating type
Receiver Tank	800 psi, 518 F	ASME pressure vessel code

TABLE I (Continued)

CHARACTERISTICS OF TEST LOOP COMPONENTS

<u>COMPONENT</u>	<u>RATING</u>	<u>NOTES</u>
Steam Separator Tank	1500 psi, 518 F	ASME pressure vessel code
Steam Condenser	6,000,000 Btu/hr	Horizontal, air cooled, finned tube
Feedwater Heaters (3)	100 kw, 1500 psi	Independent control
Piping	Schedule 80	304 & 347 Stainless Steel

3.4 Control

The loop is controlled from the console where all instruments and controls are located for operator convenience and safety. Throttling or flow control valves are air operated. Feed pump speed and condenser fan rpm are electrically controlled through mechanical linkages. A dual rheostat in each generator field varies test section power input.

Loop high-side pressure is maintained by positioning throttle valve V_1 or V_2 (Figure 3), depending upon whether a boiler or a boiler-superheater test is being conducted. Condenser fan speed (hence the amount of throttled steam condensed) determines the low-side pressure. Water flow through the main circulating pump is controlled by valve V_3 , while V_4 throttles water flow through the low flow circulating pump. During a natural circulation run, both V_3 and V_4 are closed and manual valve V_6 is left open.

3.5 Instrumentation

Water flow of less than 90 gpm is measured with various sized orifices; the differential orifice pressure being indicated on a manometer, and/or the signal from a pressure transducer recorded on a strip chart. Higher water flows are measured with a modified venturi flow tube, and the pressure differential is also indicated on a manometer or strip chart recorder.

Both orifice and venturi flow tube are used simultaneously as a double check in the somewhat more difficult steam flow measurement. Whereas only a temperature (density) correction is required for measuring water flow, compensations for temperature, pressure and quality (if applicable) are required for accurate steam flow measurement. In addition, condensing chambers must be placed in the differential pressure lines close to the flow meter to give a constant, level interface between the water and steam.

A pressure gauge reading is taken at the entrance and exit of each test section and after the condenser. Accurately-machined bourdon tube gauges are used for these pressure indications.

Pressure taps, located at four to eight inch intervals along the length of a test section, measure the drop relative to the first or "base" tap. These measurements provide an overall integrated pressure loss through the section as well as an axial pressure drop profile. This method is used on boiler, superheater, and isothermal test sections.

All pressure measuring lines are 1/4 in. outside diameter, 20 gauge stainless steel tubing. A sufficient length of tubing must be extended horizontally from the point of pressure measurement to eliminate any density variation in a vertical line. In most cases three feet of horizontal tubing is sufficient. Once past the horizontal point, the tubing must slope a minimum of one inch per foot with as few high points (potential air pockets) as possible. Means of venting must be provided for all such high points.

Thermocouples are used exclusively as temperature measuring devices. All measurements on the electrically heated rods are made with sheathed type, ungrounded thermocouples in order to eliminate an impressed emf pickup from the rods. In the high velocity steam, bare wire thermocouples are used. However, they are protected with an upstream shield to reduce any dynamic error. In all other loop locations, bare wire thermocouples are used.

Most of the sheathed thermocouples are iron-constantan because of its high millivolt output per-degree-Fahrenheit ratio.

Because of its higher resistance to corrosion, chromel-alumel is used in the bare wire thermocouples. Occasionally, for various reasons, other metal combinations are used.

An ice bath provides the cold junction for all thermocouples. The output from each thermocouple is fed to a multipoint, millivolt

recorder with the temperature being determined from conversion tables.

Measurement of electrical power into the test sections is accomplished by individual metering of the current and voltage. The millivoltage drop across a large calibrated shunt and the voltage drop across the test section terminals is recorded on individual bridge type potentiometers. The shunt millivoltage reading is converted to amps, then multiplied by the test section voltage drop to calculate the power input to the simulated fuel elements.

Steam voids in the boiler test section are determined by using a comparative gamma ray attenuation technique. A gamma ray source of either Cesium 137 or Thulium 170 and a scintillation detector are mounted on opposite sides of the test section on a movable carriage. The gamma ray intensity penetrating the test section is measured and recorded by means of a scintillation detector, a pre-amplifier, a single channel radiation analyzer (amplifier), a scaler, and a print-out device (Figure 4). Horizontal traverses are made at axial locations along the test section with the test section empty, then filled with water, and finally with the two phase mixture. From these comparative intensity measurements of the collimated gamma beam, the void fraction can be determined at any point in the test section. Typical results are shown in Figure 5.

Figure 4 ... Gamma Attenuation Detection System Block Diagram.

Figure 5 ... Typical Gamma Attenuation Equipment Data.

3.6 Shakedown

After the loop was built, it underwent a series of shakedown tests. First, the loop was cleaned with acetone and flushed out several times with distilled water. It was then cold pressurized to 2250 psi, checked for leaks, and insulated. All of the equipment was run cold at atmospheric pressure and any malfunctions were corrected.

A dummy test element was then placed in the boiler section. The dummy consisted of a 4 inch, schedule 80, flanged stainless steel pipe 10 feet long, with two copper electrodes silver-soldered to the outside surface of the pipe. The dummy was electrically insulated from the rest of the loop and connected electrically to the unipolar generators. The loop was filled with demineralized water. By generating heat in the dummy element, the loop was hot-pressurized to the Pathfinder reactor operating conditions of 600 psi and 489 F. The equipment was run under these conditions and any malfunctions were corrected. When all the equipment was made to run satisfactorily, and the Laboratory personnel had become sufficiently acquainted with the operation of the loop, the dummy test element was removed.

3.7 Pre-Test Checks

Before commencing any test program, several pre-test checks are conducted, including: a cold pressure test on the entire high

pressure side of the loop at 1-1/2 times operating pressure ... a continual circulating and flushing of the loop with demineralized water until the water conductivity is less than 10 micro-mhos ... a flange gasket insulation check ... and a low-power, low-flow run. Any leaks found during pressure checking are repaired and additional pressure tests performed until all leaks are sealed. Conductivity of the water must be low in order to restrict deposits on the heated boiler elements as well as to prevent an electrolysis effect between the positive and negative ends of the test section. If flange gasket insulation is poor, or if a direct short exists between the electrically heated section and the loop proper, a parallel current flow through the loop piping could exist, giving erroneous power input readings as well as presenting a hazard to operating personnel. A low-power, low-flow run detects improper instrumentation setups such as an open or reversed thermocouple or power-measuring lead, air in a manometer or pressure line. It also insures correct operation of all motors, pumps, and auxiliary equipment to be used during the test.

3.8 Tests Conducted

Tests performed to date include many single-rod boiler element maximum heat flux (burnout) tests under varying conditions of flow, pressure, inlet subcooling, and equivalent diameter. Larger full-length sub-assemblies tested were a four-pin, a

sixteen-pin and a variable heat input section having ten pins in the lower element, eight in the middle, and six in the upper. The culmination of the boiler program was the testing of a full scale 81-pin boiler element mock-up (Figure 2). The 81 parallel electrical paths made an extremely low overall resistance which required the full 60,000 amp output from the generators to obtain the maximum desired heat flux. This high current initially caused errors in the steam void measurements by deflecting the electron beam in the gamma ray scintillation probe. A heavy shield of laminated soft iron was placed around the probe to divert the magnetic field induced by the high d-c current. This brought the gamma ray readings back into correct proportion.

Several superheater elements were also tested in the loop. Pathfinder reactor conditions were simulated, and in many instances flow and temperature conditions were exceeded in order to bring out any weakness in the element design.

The versatility of the loop was proven in a continuous three-month superheater corrosion test. A concentric tube superheater element was subjected to Pathfinder conditions of pressure, temperature and steam flow, while a close check was kept on water and steam chemistry, particularly chloride and oxygen content. Sufficient evidence was derived from this test to verify the use of 316L Stainless Steel in the Pathfinder superheater elements.