High-Temperature Helium Loop Facility

R. D. Tokarz

September 1981

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SUMMARY

The high-temperature helium loop located at the Department of Energy's Pacific Northwest Laboratory (PNL) is a unique facility for materials testing that requires helium gas atmosphere and high temperatures. The facility was designed and fabricated at PNL to study the properties of various materials in ultra-pure flowing helium at elevated temperatures. The closed loop system is capable of recirculating high-purity helium or helium with controlled impurities. The gas loop maximum operating conditions are as follows: 300 psi pressure, 500 lb/hr flow rate, and 2100°F temperature. The two test sections can accept samples up to 3.5 in. diameter and 5 ft long. The gas loop is fully instrumented to continuously monitor all parameters of loop operation as well as helium impurities.

The loop is fully automated to operate continuously and requires only a daily servicing by a qualified operator to replenish recorder charts and helium makeup gas. Because of its versatility and high degree of parameter control, the helium loop may be applied to many types of materials research. The gas loop facility is available for testing to government as well as private entities.

This report describes the test apparatus, operating parameters, peripheral systems, and instrumentation system. The experimental capabilities and test conditions of the high-temperature helium loop are also delineated.

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HIGH-TEMPERATURE HELIUM LOOP FACILITY

The high-temperature flowing helium test apparatus is located at the Pacific Northwest Laboratory (PNL) in Richland, Washington. This helium loop facility was designed and fabricated to test various materials in pure flowing helium and temperatures up to 2100°F. Subsequently it has been used to perform creep rupture tests of gas-cooled fast reactor cladding in helium with controlled impurities. It has potential uses in the High-Temperature Gas Reactor program as well as in fusion research. Because of its versatility and degree of parameter control, the helium loop may be applicable to many other types of materials research programs.

The helium loop was built for testing materials for the Department of Energy. It is also available to government and private entities. This report has been prepared to aid researchers in many areas in identifying potential uses for the facility to provide data that is not readily available elsewhere. Of two other loop facilities in the U.S., one is much smaller, and the other is very large and expensive to operate.

A description of the apparatus, auxiliaries, and instrumentation are contained in this report, and the experimental capabilities of the loop are summarized. Also discussed are helium impurity control, system construction, modifications for the Gas-Cooled Fast Reactor Program, operation, and quality assurance.

FACILITY AND SYSTEMS DESCRIPTION

The helium loop (Figure 1) is a closed system that recirculates high-temperature, high-purity helium gas at a maximum pressure of 300 psi. The helium gas flows from the compressor through the flow orifices and flow control valves to the shell side of the regenerative heat exchanger where this gas is preheated by the hot gas returning from the test section to the compressor.

FIGURE 1. High-Temperature Gas Loop

The preheated gas flows to the main heater where the temperature is raised to a maximum of 2100°F. The horizontal test section is located immediately downstream of the heater and about 5 feet upstream of the vertical test section. After passing through both test sections, the gas enters the tube side of the regenerative heat exchanger and is cooled. Further gas cooling is provided by an air-to-gas heat exchanger that limits the gas temperature to a 640°F maximum before it re-enters the compressor. An attempterator system injects the cooler gas from the compressor into the outlet side of the vertical test section, when necessary, to precool the hot gas before it enters the regenerative heat exchanger. Remote instrumentation is provided to safely operate the system.

Eight major components of the model gas loop are as follows:

- compressor
- orifices and flow control valving
- regenerative heat exchanger

- heater
- horizontal and vertical test sections
- air-to-gas heat exchanger
- attemperator
- instrumentation.

GAS COMPRESSOR

The gas in the loop is circulated by a hermetically sealed, vertical, two-stage, centrifugal, gas-bearing compressor driven by a synchronous motor. The compressor output is varied by regulating the rotor speed from 5,000 to 24,000 rpm. The speed of the compressor rotor is controlled through a motor generator set that varies the frequency from 60 to 400 cycles. Water cooling of the compressor prevents overheating at gas inlet temperatures up to a maximum of 640°F. The compressor characteristics are illustrated in Figure 2. These curves can be used to predict the amount of pressure drop available at any flow and compressor speed. The vertical curve on the graph was obtained by decreasing the compressor speed with the flow control valve fully open.

In reference to Figure 2, if a 300-lb/hr flow rate is desired, a specimen train with a maximum pressure drop of 1300 ft helium (27.5 in. H₂O at 100°F, 150 psig) could be utilized by operating the compressor at a speed of 20,000 rpm.

ORIFICES AND FLOW CONTROL VALVING

Flow control of the primary and attemperator circuits is maintained automatically or manually. The valves are pneumatically operated from their control instrumentation through the signal from the flow-indicating orifices. Once set, the flow will remain constant unless the system temperature or pressure is changed.

REGENERATIVE HEAT EXCHANGER

The regenerative heat exchanger, a tube-in-shell type unit, cools the gas flowing from the test section to the compressor by heating the return gas from

FIGURE 2. Gas Compressor Characteristics

the compressor to the heater. The unit is a counter flow design--the gas is cooled on its passage through the central tubes while the return gas flowing through the shell is simultaneously heated. The heat exchanger is of the "U" type to reduce the problems associated with thermal expansion. The heater (Figure 3) is a two-stage concentric-type unit in which the gas passes through tubular heating elements. The first or low-temperature stage consists of twelve 51-in. lengths of nichrome tubing (0.640-in OD x 0.062-in. wall thickness) connected in series with a single-phase, 60-kW power supply. The second or high-temperature stage, which is similarly connected to another single-phase, 60-kW electrical supply, utilizes six 39-1/2 in. lengths of molybdenum

FIGURE 3. High-Temperature Gas Loop Heater

tubing (0.635-in. OD x 0.045-in. wall thickness). These tubular elements are continuously supported within discs of high-purity aluminum oxide. The second stage is located coaxially within the first stage; thus the gas flow emerging from the first stage is reversed before entering the second stage. Bypass flow is prevented by a liner between stages. Gas enters a nozzle through the side of the cylindrical shell and exits axially through the same end. The electrical and instrumentation penetrations are through the opposite end.

TEST SECTIONS

There are two test zones in the model loop where material specimens can be placed for evaluation. One test section is oriented horizontally and the other vertically.

Horizontal Test Section

The horizontal test section is located immediately downstream of the heater; thus, the maximum test temperatures are obtained in this zone. The

test zone is 66 in. long and 4 in. in diameter. Access and instrumentation penetrations are through a 4-in. Graylock fitting on the downstream end of the horizontal test section. Test temperatures within this test section will vary about 175° from a maximum of 2100°F at the heater outlet, with a gas flow rate of 400 lb/hr.

Vertical Test Section

The vertical test section is located about 5 ft downstream of the horizontal test section; therefore, the test temperatures are somewhat lower. At a 2100°F heater outlet temperature with a 400-lb/hr flow rate, the test section inlet temperature is about 1875°F, and the outlet is 250°F less. The vertical test chamber is 48 in. long with a 2-in. diameter. A reduction of the internal insulation thickness can provide an alternate 4-in. diameter near the upper zone. Entry is made through a 4-in. axial port similar to that for the horizontal section, and the gas flow past the test specimens in the vertical test section is upward.

INSTRUMENTATION

The instrument panel contains the necessary instrumentation to allow manual control of the loop system. Several of the individual systems (i.e., flow-temperature-pressure) have automatic steady-state operational capability, and a completely automatic system has been established. An annunciator system is provided with an automatic telephone dialer. If an unsafe condition exists, the gas loop is shut down and a phone call automatically is made to the security personnel. The security personnel call one of the qualified operators to make repairs and restart the loop.

Data collection is accomplished by hard copy recording of 46 various sensors, including flow, temperature, and pressure. Every measured parameter has at least two independent trip functions, and many parameters have high and low trips. These signals provide a complete record of the gas loop operating characteristics.

AUXILIARY SYSTEMS

In addition to the eight major components of the gas loop, there are three systems--gas purification, bypass cleanup, and gas monitoring--which can be used for preparing, maintaining, and monitoring the helium gas purity.

Gas Purification System

To properly evaluate the effects of high temperatures on material properties specimens, it may be necessary to maintain the specimens within a high-purity inert gas atmosphere. Since its total impurities can be as high as 50 ppm, commercially available Grade A helium does not meet the purity requirements for this testing. Therefore, a helium purification system was developed to provide the high-quality gas needed for the model loop operation.

The purification system is capable of generating ultra-high-purity helium gas with less than 1 ppm total impurities (including water) from commercial Grade A helium.

Bypass Cleanup System

Although high-purity helium gas is initially charged into the system, during high-temperature loop operation this gas will pick up contaminants caused by outgassing and leakage in-flow. A bypass cleanup system (Figure 4) has been installed to maintain the gas quality at a high level during system operation. A small gas flow from the circulator outlet is directed through the cleanup system and returned to the circulator inlet where it mixes with the main loop flow. This system is provided with dual molecular sieve towers; this system allows a change to regenerated towers when the gas analysis indicates the quality is decreasing. The alternate towers can be regenerated without an interruption in loop operation.

Gas Monitoring System

The ultimate success of a test program conducted with a closed gas loop system depends upon the ability to monitor the quality of the recirculating gas within the system. A sample gas from the loop is piped to sensing instrumentation located immediately adjacent to the compressor piping. This

FIGURE 4. Bypass System

instrumentation consists of two moisture sensors: An EG&G dew point sensor and a Panametrics dew point sensor with three sensing probes. These moisture sensors are used for indication only. The gas is also piped to two Thermox sensors. In the absence of oxygen, carbon monoxide, and carbon dioxide these sensors read directly in hydrogen-to-water ratio. In addition to these sensors, a gas chromatograph uses an ultrasonic detection system and is calibrated to read the hydrogen, oxygen (if any), nitrogen, methane, and carbon monoxide in the sample gas. The readout of these systems is recorded by the operator in a log book.

HELIUM IMPURITY CONTROL

The gas loop has the capability to be run with selected impurities. The present program calls for specific levels of hydrogen and water. To operate the loop with these specific impurities the following procedures are implemented. The bottled makeup gas for the loop is purchased with a specified level of hydrogen mixed with the helium. Portions of the bypass cleanup system are then utilized to add or subtract water or to convert hydrogen to water.

Hydrogen from the gas loop can be pumped through a cold copper-oxide tower which contains a small quantity of water, thereby increasing the water level in the loop and leaving the hydrogen level as is. The gas can be pumped through a hot copper-oxide tower where the hydrogen is consumed and water is generated, thereby lowering the hydrogen level and raising the water level. To this later combination can be added a molecular sieve tower that will remove the water, thereby lowering both hydrogen and water. If the water level is too high, the molecular sieve tower can be used alone to lower the water.

Once the desired absolute levels of hydrogenated water are achieved, then impurity control at that level is accomplished by uniform continuous makeup from the supply bottles and a micrometer flow valve which allows a minute quantity of gas to flow through the hot copper-oxide tower. This flow is adjusted experimentally until the conversion of hydrogen to water in the copper-oxide tower is equal to the conversion water to hydrogen in the heated section of the gas loop. Recent test runs with the gas loop indicate that the ratio of hydrogen to water in the loop can be set and maintained for hundreds of hours of continuous operation. However, if the oxidation of the test samples were to vary significantly with time, this operating parameter would have to be continuously adjusted to maintain the same ratio.

SYSTEM CONSTRUCTION

The model loop has been fabricated from a considerable array of materials. Originally, the system employed a double containment arrangement where the cooler shroud piping was pressurized to relieve the stresses on the inner and much hotter primary piping. That system has since been replaced with 300 series stainless steel containment piping with internal metal foil insulation that makes double containment unnecessary. All portions of the loop between the regenerative heat exchanger and the vertical test sections are now insulated with metal foil insulation and have water cooling jackets or tubes on the outer surface. This insulation is composed of 2-mil-thick Inconel foil sheets with a corrugated pattern to provide greater strength and a minimum contact area. The foil sheets are concentrically wound on a liner fabricated of superalloy materials (Haynes 25-Hastelloy X). A 300 series stainless steel

outer liner is pinned through the foil sheets to the inner liner and provides a structurally sound, uniformly thick insulation.

The sections are fitted to each other with labyrinth-type joints which permit adequate space for thermal radiation to the outer containment member. The water jackets and/or cooling tubes, fixed to the outer containment piping, provide system integrity by keeping the containment surface cool and thus within allowable stress values. Bleed ports have been installed on all cooling jackets to prevent hot spots from steam vapor buildup. The model loop piping is supported by conventional pipe hangers and rollers from a structural steel framework to reduce the effects of temperature stresses caused by thermal expansion and contraction. To provide maximum safety for operating personnel, the loop is located in a separate room adjacent to the instrumentation and auxiliary systems.

MODIFICATIONS TO THE GAS LOOP FOR THE GAS-COOLED FAST REACTOR (GCFR) PROGRAM

The gas loop was originally designed to be operated with ultra-pure helium and was manned 24 hours a day during its test life. The expected duration of some of the GCFR tests made round-the-clock manning prohibitively expensive. Therefore, one of the first decisions made in this program was to update the control instrumentation and add the necessary safety trips to allow unattended operation of the gas loop for periods as long as three days. This was accomplished by the purchase and installation of temperature data loggers with over-temperature trip functions, a digital readout with high and low trips for the compressor speed control system, and a 24-point annunciator. All the trips from the many recorder controllers as well as the new instrumentation were added to the annunciator. The annunciator trip was then coupled to an automatic dialing device which calls the security patrol at the Department of Energy's Hanford Reservation. Meanwhile any trip function shuts down the gas loop, leaving it in a safe condition. When the Hanford security patrol receives a phone call, they in turn call one of the qualified loop operators to determine the cause of the trip, make the necessary repairs, and restart the gas loop.

The instrumentation necessary to measure helium gas impurities was added to the system.

HELIUM IMPURITY GENERATION, CONTROL, AND MEASUREMENT

The methods of generation and control of the hydrogen and water levels have evolved over the life of this program largely from experimental gas loop runs. The instrumentation used to measure the gas impurities has been evolved during the same period. Experience shows that all components, the gas loop piping as well as the test train, must be conditioned to a given impurity ratio before any stable condition can be maintained. In the early portions of this program the rapid changes in reactivity in the loop caused many problems and several control modifications which were inadequate to provide the proper response.

Over the past five years we have evolved the following methods for generation and control of the impurity ratio in the gas loop. For example, it is specified that a creep rupture test is to be conducted at a specific hydrogen-to-water ratio. The empty loop is evacuated and backfilled with helium with a level of hydrogen approximately 50 ppm higher than the desired level for the test run. The loop is started and taken to operating temperature. The impurity ratio is constantly monitored with the Thermox sensors, and the absolute value of the hydrogen is measured periodically by the chromatograph. The parameters are adjusted by the various control functions until a stable control point is reached and maintained. The impurity ratio of the last run will determine how long it will take the loop to achieve a stable operating condition. If there is to be a large new surface area in the test train, then this process may have to be repeated on startup of the test to condition the test train to the impurity level. This process of conditioning can take from 50 to 100 hours of loop operation.

Once the loop conversion or oxidation rate has become stable and the absolute values of water and hydrogen are in the vicinity of specified values, the bypass flow is diverted through the hot copper-oxide tower. The flow is adjusted so that the conversion of hydrogen to water in the tower is exactly equal to the opposite conversion rate in the heated portion of the gas loop.

Given that the above balanced condition can be created for any ratio, then by knowing the hydrogen level into the copper-oxide tower and the flow, one can determine the total conversion rate in the gas loop. Running the gas loop at the same conditions, with and without the test train, will provide a definitive reactivity rate for the test train surface. This data may be of practical use. An attempt has been made to obtain preliminary data of this nature in tests conducted to date.

Impurity measurement is accomplished with the aid of two types of moisture sensors. The EG&G dew point sensor, Model 440, is a cooled mirror surface which is sensed by an LED and photo cell system. This dew point sensing system is coupled to a proportional controller which controls the mirror surface temperature. This model will withstand the gas loop pressure of 300 psi, so initially it was piped across the compressor. The readings taken in this configuration were totally inconsistent with known operating conditions and could not be correlated to any believable values of moisture which could exist in the gas loop. After many months of trying to obtain real readings, the EG G was repiped from a sample line just downstream of the regenerative heat exchanger and operated at atmospheric conditions. Since that time its readings have been consistent and close to the moisture levels as calculated from the chromatograph and Thermox readings, except at moisture levels of 30 ppm and below.

The Panametrics dew point sensor is an aluminum-oxide layer on aluminum, excited by a high-impedance source. The change in impedance of the oxide layer is related to the dew point electronically. There are three sensors in series with the gas stream, and actual moisture content is determined by reading calibration curves for each sensor. This device also is stable and reasonably good above 30 ppm. But below that point it characteristically reads about only one half the moisture level of the EG&G moisture sensor. Since neither of them can be made to consistently agree with calculated values obtained from the calibrated Thermox and chromatograph, these sensors are used only for indication purposes.

The Thermox oxygen analyzer consists of a ceramic cell coated with platinum and housed in a temperature-controlled oven. At the oven temperature of

975°C a voltage is generated across the ceramic cell which is proportional to the difference between the oxygen on the outside of the cell (room air) and the oxygen on the inside of the cell (sample gas). In the absence of oxygen the cell then becomes sensitive to the ratio of carbon dioxide to carbon monoxide and to the ratio of hydrogen to water. In the gas loop there is no oxygen or carbon monoxide, and therefore the Thermox is sensitive only to the hydrogen-to-water ratio.

The Thermox cell is calibrated by using a certified mixture of helium and hydrogen. The hydrogen level is selected as representative of that level used in the gas loop to achieve the specified ratio. A water pressure saturator is contained in an ultra-low-temperature refrigerator, and the temperature of the refrigerator is set to various low values. The helium with hydrogen gas is passed over ice at the specified temperatures and then through the Thermox cells. With the hydrogen and water levels known from the input systems, a calibration curve is drawn for each Thermox sensor. This curve approximates a straight line on a semi-log graph. The response time of the Thermox sensing cells is very slow. Because of this slow response one cell is left on at all times, monitoring the gas loop during test runs.

The chromatograph used with the gas loop is a Tracor Model 150G with an ultrasonic sensor. The chromatograph consists of two towers, a porapak, and a molecular sieve tower. These are contained in temperature-controlled ovens at 75°C and in our configuration are run in series. The chromatograph is calibrated by injection from one of the two calibration gas cylinders. These cylinders contain different trace quantities of the following gases in a helium carrier: hydrogen, oxygen, nitrogen, methane, and carbon monoxide. The accuracy of the chromatograph in this nonlaboratory condition is approximately ± 35 ppm for hydrogen at a base level of 350 ppm. At maximum sensitivity the chromatograph has never detected the presence of any carbon monoxide or methane in the gas loop.

GAS LOOP PREPARATION, STARTUP, AND OPERATION

Prior to startup all instrumentation is calibrated and all safety loop trips are tested. The gas loop is evacuated using a roughing pump and an ion

pump down to 10 microns. Then the loop is backfilled with mixed gas containing the specified level of hydrogen. The creep rupture samples are pressurized to 1300 psi. The loop makeup gas pressure is set to 125 psi.

Loop startup begins by starting the gas bearing compressor and turning on the nichrome heater. Power to the heater is increased each 5 minutes to achieve a heatup rate of 2 to 3 degrees per minute. Moisture monitoring begins immediately, and if moisture in the loop is high, the dryer towers are placed on line to remove the moisture. The test train sample pressure is monitored. At a loop temperature of 550°C the creep rupture samples pressure should be 80% of final pressure.

As loop temperature increases, the oxygen is consumed, and the Thermox sensors begin to measure the hydrogen-to-water ratio. During this heatup period (1.5 to 2 hours) the various impurity control functions are implemented as required to achieve the desired levels of hydrogen and water. When the loop temperature achieves the 550°C range, the heater is adjusted to maintain that temperature while the impurity ratio is adjusted to the desired level for the specific test. Flow through the hot copper-oxide tower is set from previous experience, and the various gas-measuring instruments are monitored to determine if a stable ratio can be maintained. The loop is held at this temperature until stability is achieved; then the temperature is increased to 650°C and the temperature control is placed in automatic. The test train pressures are checked and filled or reduced as required during this period. The loop operation is monitored and adjusted for as long as required to achieve a stable gas impurity ratio. The loop is then monitored each day and adjustments are made as required until sample failure occurs.

QUALITY ASSURANCE REQUIREMENTS

The normal PNL Quality Assurance requirements have been augmented with additional criteria to meet the QA Standard RDT F-2-2.

The program has received two full audits as well as periodic minor audits and has been found to be in compliance with F-2-2 requirements.

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