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HIGH-TEMPERATURE HELIUM LOOP FOR NUCLEAR PROCESS HEAT STUDIES

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ABSTRACT

An ERDA-sponsored study and evaluation program for the development of a very high-temperature gas-cooled reactor (VHTR) as a source of industrial process heat has been in progress at LASL since 1974. The reported conceptual design study of a high-temperature helium test facility is a part of the evaluation of experimental support requirements. The experimental design presented is that for a test of a full-scale bundle of an intermediate helium-to-helium heat exchanger. This experiment would require the maximum test capability expected for process equipment development testing in such facilities, and therefore also provides appropriate specification information on facility equipment. The analysis presented indicates that a regenerative loop design employing a resistively heated graphite helium heater could accomplish the test objectives. The power requirements for this level of testing are within the capability of existing equipment at LASL. Other facility requirements such as heat dump capacity, gas handling capability, and test cell configuration are also discussed.

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I. INTRODUCTION

The energy required for industrial process heat and process power is a major fraction of the primary energy demand in an industrial nation. Industrial users in the U.S. are the largest single category of consumers and they account for about 40% of the total primary energy consumption. This industrial energy demand is presently supplied by fossil fuel sources, primarily natural gas and petroleum, with about a three-to-one ratio between process heat and process power uses. Natural gas is used to supply about half of this process heat demand, petroleum a little more than a quarter, and coal a little less than a quarter. The recent rapid escalations in petroleum and natural gas prices have had a major economic impact on industrial users; and

there are concerns about adequate long-term supplies of these fuels, foreign or domestic, at any price. The present U.S. primary energy demand cannot be met by the domestic supply of these fuels. The projections for the future supply and demand situation vary somewhat quantitatively depending on the scenario of use proposed, but they all show an increasing demand and a diminishing supply with a growing deficit between them over the next twenty-five or so years. It is obvious that domestic substitutes for petroleum and natural gas and other alternate primary energy sources must be developed if the national energy and economic future is to be secure.

The major U.S. process heat demand is for processes in chemical production, primary metal refining, petroleum refining, papermaking, and ceramics. Processes in chemical production, primary metal refining and petroleum refining require large high-temperature heat sources. The developing technologies for the production of synthetic liquid and gaseous fuels from coal, for the recovery and refining of oil shales and tar sands, and for hydrogen production by the thermochemical decomposition of water have potential requirements for very large (an order of magnitude larger) high-temperature heat sources. Possible alternate primary energy sources for these larger industrial applications include solar reactors, nuclear fusion reactors, nuclear fission reactors, and coal. The development prospects for appropriate solar and fusion reactors are so long-range and indefinite that they cannot be considered as serious candidates before the year 2000. An expanded utilization of the large domestic reserves of coal and uranium as fuels and for the production of synthetic liquid and gaseous fuels could meet the predicted domestic energy supply and demand deficit. The development of the appropriate concepts for their utilization is sufficiently advanced so that they are the only potential alternate sources that could be available in this time period. As a result, industrial users will have to rely more and more on coal and nuclear fission energy sources for process heat and process power to the year 2000. The requirements for synthetic liquid and gaseous fuels for residential and commercial uses and transportation will also increase as the supplies of domestic petroleum and natural gas diminish.

The nuclear fission reactor has received consideration as an industrial process heat source at various points in its development that date back to the late 1940's. Those reactor concepts that have been commercialized for steam-cycle electric power generation have an operational temperature range, 588-978 K (600-1300°F), that is too low to meet the source requirements of the larger process applications. When such reactors are large enough to be economically advantageous as a heat source for process steam (above 1200 MWt), they are much too large for the average user load. The problems of centralizing many steam users to accommodate the large output of a single reactor are magnified by the present low availability history of commercial reactors. As a result, these reactor concepts do not have adequate potential advantages to justify their development as process heat sources. The graphite moderated gas-cooled reactors presently under development are, however, potentially capable of producing the highest process temperatures (about 1300 K) that could be required for these larger high-temperature process applications. The development of this reactor concept coupled with the current world petroleum and natural gas situation has produced serious reassessments of the technical and economic aspects of the development of nuclear-process heat systems in industrialized countries. The incentives for the development of nuclear sources for process heat are the same for all industrialized countries; the schedule and timing of a development plan is more a function of the

specific national energy resource situation. Major programs in support of the development of nuclear-process heat systems began in the late 1960's in the Federal Republic of Germany (FRG) and Japan, due primarily to their petroleum and natural gas import requirements and corresponding lack of adequate domestic energy resource reserves.

In the U.S., the reevaluation of the nuclear fission reactor as a source of industrial process heat began in 1974 with a study program to assess the national needs and incentives for the development of a very high-temperature gas-cooled reactor (VHTR) as a heat source. This assessment program was funded by the Energy Research and Development Administration (ERDA) and produced a preliminary plan for the VHTR-process heat program in early 1976. The objective of the program is the development and demonstration of the necessary technology for the application of the heat derived from the nuclear reactor to high-temperature industrial chemical processes. Only those processes that have high-temperature primary energy requirements considered large enough for an economic reactor source application (about 2000 Mwt) have been included in the preliminary technical and economic evaluations. The candidate processes include iron ore reduction, hydrogasification-liquefaction of coals, production of chemicals using hydrogen, steam gasification of coals, and hydrogen production by the thermochemical decomposition of water.

The planned U.S. VHTR-process heat program will have the following major technical units: high-temperature materials development, advanced coated particle-graphite fuels development, component-system design and analysis, component development testing facilities, and environmental and safety research.¹ A technical development plan for a VHTR-process heat demonstration plant is being prepared by ERDA in conjunction with industrial reactor contractors and national laboratories. The materials development activities are scheduled to begin in calendar year 1976. The evaluation of commercially available materials for VHTR-process heat systems and the assessment of development requirements for new materials are planned. The fuels development program is in progress at the Los Alamos Scientific Laboratory (LASL). Advanced fuels and fuel forms for high-temperature operation in helium are under investigation. This work is based, in part, on the considerable expertise developed at LASL in the space reactor and ultrahigh-temperature gas-cooled reactor programs. Fabrication methods for advanced coated fuel particles and extruded graphite fuel elements are being developed,² and performance tests of developed fuels and fuel elements are planned. Component and system design began in 1974 with the preparation of conceptual design studies of the VHTR as a process heat source by industrial reactor contractors.³⁻⁵ Additional conceptual design studies of heat transport system options and plant layouts by the same contractors are scheduled for completion in mid-1976. The results of these studies will be utilized in the evaluation and analysis of the economic, safety and engineering design aspects of VHTR-process heat systems. A design analysis program was initiated at LASL in 1975. Analytical methods are being developed for the necessary technical and economic analysis of component and system designs and to provide guidance for research and development activities.⁶

A common conclusion in all of the studies cited is that materials selection, qualification, and the related development of component design and fabrication techniques will constitute critical milestones in the program to develop a high-temperature nuclear process heat system, even at the 1144 K (1600°F) process heat level. In view of the long lead time associated with these tasks and the fact that this work will be required regardless of the

specific industrial process ultimately selected for a demonstration plant, it is obvious that a high-temperature helium test facility should be developed as soon as possible to provide timely testing of system concepts, hardware configuration concepts, and hardware components.

II. THE EXPERIMENT DESIGN

A major difficulty in this exercise to scope possible test facility requirements is the lack of a specific demonstration plant plan or unique conceptual designs of components. It is necessary, therefore, to assume a direction for the development of the nuclear process heat system, establish general requirements, and proceed accordingly. When the present state of material technology is considered, the maximum heat transport system temperature is limited to about 1223 K (1742°F); this would occur in the primary helium circuit at the reactor outlet. The helium temperature, in turn, could produce a possible process temperature maximum of 1144 K (1600°F). The materials development program for equipment to handle helium at temperatures much above this level would require a considerable period of time; the selection of the upper temperature limit is reasonable and realistic on this basis alone. From the process standpoint, the temperature is adequate for most candidate processes under consideration.⁷

Two additional test facility parameters require special consideration in this scoping exercise; they are the flow and heat transfer rates. In order to make a preliminary estimate of a desirable magnitude for these, the three conceptual nuclear process heat system designs prepared by General Electric (G.E.),³ General Atomic (GA),⁴ and Westinghouse Astronuclear Laboratory (WANL)⁵ under contract to the U.S. Atomic Energy Commission were utilized. The G.E. and WANL concepts both employ intermediate heat exchangers in their reference plant designs whereas the GA concept does not. A very simplified schematic of a VHTR system for process heat is shown in Fig. 1. One appropriate task for a high-temperature helium test facility could be the development testing of the intermediate heat exchanger. A limited table of heat exchanger parameters taken from the G.E.³ and WANL⁵ design reports is provided in Table I.

Reviewing Table I, it is apparent that, in general, a component such as the intermediate heat exchanger (IHX) would not be tested in full scale because of economic constraints. Multidimensional scaling of a complete component is generally not acceptable because the large dimensional differences involved can lead to breakdowns in similitude. Full-scale testing of a module of the complete component appears to be the most appropriate type of developmental test for components such as the IHX. A test module for a heat exchanger of the tube-in-shell design would consist of a number of tubes (tube bundle) housed in a shroud in such a fashion as to maximize the similarity of the test module to the full-scale heat exchanger. If the High Temperature Helium Test Facility (HTF) is to have the capability of testing at the module level as a maximum requirement, this test would establish the maximum operating characteristics for most of the components of the HTF.

In order to gain further insight into the size of components required for the test of a module of a heat exchanger, consider the highly simplified test loop shown schematically in Fig. 2. This loop is designed to accommodate one module of the G.E. conceptual design IHX. The working fluid (helium) is heated to 1223 K in a heater and flows through the primary side of the module of the IHX under test whereupon this fluid flow is split into a bypass loop

TABLE I

GE Concept

Pressure - 4137 MPa (600 psia)	
5 IHX's @ 272 MW each	
IHX Type - Counterflow-Tube-In-Shell	
Helium Temperature: Primary - 905-1223 K (1171-1742°F)	
Secondary - 700-1190 K (800-1685°F)	
Material (Tubes)	Incolloy 617
Bundles	139 tubes/bundle-72 bundles/IHX
Primary Circuit Flow Rate/IHX	1.64×10^2 kg/s (1.3×10^6 lb/h)
IHX Flow Rate/Bundle	2.27 kg/s (5.0 lb/s)
Secondary Circuit Flow Rate/ Bundle	1.47 kg/s (3.23 lb/s)

Westinghouse Concept

Pressure - 6.895 MPa (1000 psia)	
5 IHX's @ 315 MW each	
IHX Type - Counterflow-Tube-In-Shell	
Helium Temperature: Primary - 1283-704 K (1850-808°F)	
Secondary - 644-1200 K (700-1700°F)	
Bundles	169 tubes/bundle-24 bundles/IHX
Primary Circuit Flow Rate/IHX	103 kg/s (0.82×10^6 lb/h)
IHX Flow Rate/Bundle	4.30 kg/s (9.49 lb/s)
Secondary Circuit Flow Rate/ Bundle	4.51 kg/s (9.95 lb/s)

Fig. 1.
VHTR-process heat system schematic.

Fig. 2.
Schematic simplified test loop.

and a primary loop. The next component in the primary loop, termed here the conditioning heat exchanger, adjusts the temperature of the fluid to match the inlet temperature of the secondary side of the intermediate heat exchanger module. A helium circulator for the primary flow is located at the next stage of the loop, circulating the fluid through the secondary side of the IHX back to the heater inlet where the fluid is mixed with the bypass flow.

It is apparent that, at least conceptually, such a regenerative loop could be used to test an intermediate heat exchanger module with considerably lower input power at the heater than the heat flux delivered in the test heat exchanger. Temperatures, helium flow rates, and primary side pressure could be matched exactly to the component operating conditions; however, the secondary side inlet pressure would be dictated by the pressure drop in the loop components. Some adjustment of the secondary inlet pressure (upwards) could be achieved by throttling but there would be an attendant increase in pumping power requirements and costs. The constraint on the secondary side pressure is one of two major constraints associated with such a loop design; the second being the requirement that both the primary and secondary side of the heat exchanger utilize the same working fluid stream.

In order to investigate the feasibility and utility of this type of loop design, the startup transient of such a system was numerically simulated. The results of these calculations are presented graphically in Fig. 3, where it can be seen that approximately 90 minutes are required for the modeled system to reach design operating conditions. In the following sections of this report, these considerations are treated for a more realistic loop design in greater detail.

The loop design illustrated in Fig. 2 would be difficult to realize physically since the required circulator operating temperatures are excessively high for current design practice. This difficulty could be surmounted by employing recuperators in both the primary and bypass loops as shown in Fig. 4 (the reference experiment). A thermal penalty is incurred since the heat lost in the dump required in the bypass loop to establish the approach temperature difference must also be provided by the heater. No additional thermal penalty is incurred in the primary helium loop since the same type of loop conditioning heat exchanger shown in Fig. 2 would provide an adequate temperature difference for the primary recuperator. Figure 5 is a schematic of a possible physical arrangement of the components of the reference experiment. A listing of the components and component requirements for this loop design is presented in Table II. The major components are discussed in the subsections following.

A. Heater

The 1149 K (1600°F) process loop requires a heater capable of operating at 4.137 MPa (600 psi), providing 1.68 MW to helium gas with a design outlet temperature of 1223 K (1742°F). Heating of the gas could be accomplished in several different ways:

1. convection/conduction
2. direct coupling
3. radiation.

The convection/conduction option would be implemented using flow over heated elements. One approach employing this technique would be to flow the helium over resistively heated graphite elements; and since considerable expertise exists in this technology at LASL, it is a likely candidate. A second technique employing this option would utilize a rather conventional gas-fired furnace. This technique may have advantages deriving from the fact that

furnaces of this design are currently operational in process applications with operating temperatures similar to those required in the helium test loop.

Direct coupling involves plasma generation which could include arcs of both dc and ac types, induction-generated plasma, as well as laser-generated plasma. Each of these techniques results in higher temperature plasmas than required; however, mixing could be used to adjust the bulk flow temperature. Direct current arcs generally have excessive electrode erosion leading to relatively short operating lifetime as well as contamination of the working gas. Three phase ac arcs have been operated at the Arnold Engineering and Development Center (AEDC), Tullahoma, Tennessee, during the past five years. These arcs have considerably lower flow rates than are required for the loop. In addition, these arcs have a relatively short electrode lifetime, on the order of eight hours.

AEDC is also currently testing a 5-MW induction heater designed for operation on air. Heaters of this type are generally unrestricted in operating lifetime and have the advantage of direct coupling to the gas allowing the use of a cool cover gas in the neighborhood of the containment wall resulting in an extended lifetime and low contamination rates for the working gas. It has been estimated that development of such a heater for the high-temperature helium test loop would require approximately two years.⁸

Fig. 3.
Calculated start-up transients.

Fig. 4.
Schematic reference experiment loop design.

Fig. 5.

A possible physical arrangement for the reference experiment.

Radiative coupling to helium would, of course, involve a radiating element and absorption by the gas. For the temperatures and pressures of interest, the absorptivity of helium is too low to be of practical interest even if a suitable radiation source is available. Seeding of the gas to enhance the absorptivity does not appear practical.

Reviewing the candidate heating techniques, it appears that convective/conductive heating of the helium working fluid using either resistively heated elements or conventional gas-fired furnace technology are the primary candidates for utilization in the high-temperature helium test loop design for the following reasons.

1. The conventional gas-fired heater is representative of an existing technology, and the components have demonstrated long lifetimes (on the order of five years).
2. Resistive heating furnaces have been used at LASL to test nuclear fuel elements over the past 15 years. These furnaces operated for ten hours producing gases at temperatures in excess of twice those required for the helium test

loop. Design of a similar furnace matched to the required operating conditions and providing long life appears feasible using the technology developed in the fuel testing program.

This second option has been investigated in some detail. A steady-state computer analysis of a resistively heated graphite heater element design has been conducted; a heater design sized to the reference experiment was analyzed as well as a smaller unit based on the original Rover element geometry.

The larger design incorporates seven hexagonal elements, each having nineteen flow channels 0.01 m in diameter. The elements have a web thickness of 0.00325 m, a void fraction of 0.516, and an overall length of 1.5 m. Fabrication of type AAQ1 graphite was assumed and its known physical properties were used in the calculations. A plot of the electrical resistivity of this graphite as a function of temperature is shown in Fig. 6. Superimposed on this plot are plots of two empirically determined equations which fit the electrical resistivity data in the temperature regime of interest. The calculated operating map for the heater required in Loop Design 2 is shown in Fig. 7, where calculated pressure drop is plotted as a function of heater electrical power with the current as a parameter. The flow channel diameter (DE) and outlet temperature (T_{outlet}) are also shown as parameters. Similar results for the heater design with a 20% reduction in helium flow are shown

TABLE II

COMPONENT REQUIREMENTS - 1144 K (1600°F) PROCESS LOOP

HEATER

Flow Rate: 2.268 kg/s (5 lb/s)
 Q to Gas: 1.68×10^6 W
 Inlet Temp: 1080 K (1485°F)
 Outlet Temp: 1223 K (1742°F)

INTERMEDIATE HEAT EXCHANGER

Flow Rate: Primary - 2.268 kg/s (5 lb/s)
 Secondary - 1.465 kg/s (3.23 lb/s)
 Q Design: 3.73×10^6 W
 1 Bundle of 72 Tubes
 Helium/Helium
 Inlet Temp: Primary - 1223 K (1742°F)
 Secondary - 700 K (800°F)
 Outlet Temp: Primary - 906 K (1171°F)
 Secondary - 1192 K (1685°F)

PRIMARY LOOP CONDITIONING HEAT EXCHANGER

Fluid: Helium/Water
 Flow Rate: Primary - 1465 kg/s (3.23 lb/s)
 Q: 1.57×10^6 W
 Inlet Temp: Primary - 795 K (971°F)
 Outlet Temp: Primary - 589 K (600°F)

PRIMARY CIRCULATOR

Fluid: Helium
 Flow Rate: 1.465 kg/s (3.23 lb/s)
 Operating Temp. Helium: 589 K (600°F)
 Pressure Rise: Estimated 207-241 kPa (30-35 psi)
 Operating Pressure (Outlet): ~ 4.137 MPa (~ 600 psi)

BYPASS CIRCULATOR

Fluid: Helium
 Flow Rate: 0.803 kg/s (1.77 lb/s)
 Operating Temp: 589 K (600°F)
 Pressure Rise: Estimated 103.4 kPa (15 psi)
 Operating Pressure: ~ 4.137 MPa (~ 600 psi)

PRIMARY RECUPERATOR

Fluid: Helium
 Flow Rate: 1.465 kg/s (3.23 lb/s)
 Q: 0.84×10^6 W
 Inlet Temp: Primary - 906 K (1171°F)
 Secondary - 589 K (600°F)
 Outlet Temp: Primary - 795 K (971°F)
 Secondary - 700 K (800°F)

SECONDARY RECUPERATOR

Fluid: Helium
 Flow Rate: 0.803 kg/s (1.77 lb/s)
 Q: 1.2×10^6 W
 Inlet Temp: Primary - 906 K (1171°F)
 Secondary - 589 K (600°F)
 Outlet Temp: Primary - 616 K (650°F)
 Secondary - 878 K (1121°F)

SECONDARY LOOP CONDITIONING HEAT EXCHANGER

Fluid: Helium/Water
 Flow Rate: Primary - 0.803 kg/s (1.77 lb/s)
 Q: 0.116×10^6 W
 Inlet Temp: Primary - 616 K (650°F)
 Outlet Temp: Primary - 589 K (600°F)

in Fig. 8. It is apparent that very high current levels would be required to attain the desired power levels for this design heater if the graphite element electrical resistivity is that of AAQ1 (Fig. 6). Significant increases in electrical resistivity are possible, factors of 3 to 4; however, other important properties also change as the graphitization temperature is reduced. An appropriate combination to yield the desired resistivity is considered within the present state of the technology, but some experimental effort would be required to develop the proper mixture. Assuming that the electrical resistivity of

AAQ1 (Fig. 6) can be doubled (a conservative factor of 2), the calculated operating map for the heater (Fig. 9) shows a significant change in the applied current to achieve the desired conditions of Loop Design 2. By controlling the electrical resistivity, it is therefore possible to design graphite heater elements for a wide range of input power levels and helium flow rates. As an example, the calculated operating map for a heater employing a bundle of seven of the original Rover design elements

Fig. 6.
Resistivity of AAQ1 graphite.

Fig. 7.
Heater operating map, AAQ1 graphite
reference experiment.

Fig. 8.
Heater operating map, AAQ1 graphite -
80% flow reference experiment.

[9 holes of 0.00254 m diam (DE), hexagonal shape of 0.1905 m across the flats, 0.4 void fraction (VF), 1.5 m in length (L)] is shown in Fig. 10. Thus, interchangeable heater elements for various experimental requirements are possible and would give flexibility to the loop's utility.

The temperature distribution in the axial direction along the graphite elements in the design operating mode (1080.6 K inlet temperature, 1223 K outlet temperature) is shown in Fig. 11. The possibility of unstable operation due to the fact that the first third of the elements are operating in a temperature regime where the curve of resistivity as a function of temperature has a negative slope (shown as the shaded area in Fig. 11) indicated that additional study of this aspect was warranted. A time-dependent computer calculational model of a two-channel system was therefore developed in order to investigate the thermal stability of the heater design. Perturbations involving geometry and initial temperature were investigated and the results are summarized in Table III. In all cases, the system was found to converge uniformly on a stable operating condition; however, in the cases involving geometric asymmetries, the stable operating condition involved significant graphite temperature differences indicating a potential thermal stress problem. Although this aspect requires further study, it is not treated in this report; thermal stress analysis would be required for heater design.

Fig. 9.

Heater operating map, double graphite electrical resistivity reference experiment.

Fig. 10.

Heater operating map, Rover elements.

Fig. 11.

Temperature distribution in graphite elements.

TABLE III

STABILITY STUDY

Nominal Configuration: Two parallel graphite elements of length 1.5 m, with graphite cross-sectional area $7.37 \times 10^{-5} \text{ m}^2$, and flow channel cross-sectional area $7.85 \times 10^{-5} \text{ m}^2$. The two graphite elements are thermally connected for conduction along their length by a width equal to 1/6 the external diameter of the elements.

Types of perturbation investigated:

1. 25% increase in the initial temperature of graphite element #1.
2. 19% reduction of flow area in channel #1.
3. 20% reduction of graphite cross-sectional area in graphite element #1.
4. 50% decrease in area for conductive coupling between the two graphite elements.

Simulation

Run	Perturbation	Results
1	1	Converges to same operating temperature for both elements.
2	1 & 2	Converges to same operating temperatures for both elements.
3	1, 2 & 3	Converges to a stable operating condition with graphite near the exit of channel #1 and the fluid exiting channel #1 approximately 25 K hotter than channel #2.
4	1, 2, 3 & 4	Converges to a stable operating condition with a 30 K temperature difference between the two channels as described in 3.

B. Heat Exchangers

The loop design requires four heat exchangers in addition to the experimental item to be tested. Two of these are helium/helium recuperators and two are helium/water loop conditioning heat exchangers. In the bypass loop, the recuperator is used to drop the helium temperature to an acceptable level for the circulator; whereas the conditioning heat exchanger is used to provide the appropriate approach temperature difference to the recuperator. The heat rejected by the conditioning heat exchanger is lost and therefore should be held to a minimum. On the other hand, as the approach temperature difference is reduced, the physical size of the bypass recuperator must increase. The appropriate trade-off must be evaluated and will require additional effort in design studies.

The heat exchange objective in the primary loop is not only to provide the appropriate inlet helium temperature for the circulator but also to provide the appropriate secondary helium temperature at the test section inlet. The amount of heat rejected by the primary loop conditioning heat exchanger is dictated by the difference between the outlet temperature of the primary flow from the test heat exchanger and the secondary inlet temperature of the test heat exchanger. It provides an adequate approach temperature difference for the

recuperator. It should be pointed out that even if the recuperator were not used, resulting in a higher circulator operating temperature, the same amount of heat would have to be rejected. All four of these heat exchangers appear to be well within the state-of-the-art and no special development problems are anticipated.

C. Circulators

A detailed study of the required helium circulators was not considered necessary at this point. The 589 K operating temperature assumed seems conservative in view of the fact that this was the design temperature used for the UHTREX circulators which are now more than ten years old. Mass flow and pressure rise greater than those required here have been available in helium circulators utilized previously for various gas-cooled reactors. In spite of the fact that the circulators appear to be within the state-of-the-art, they will be expensive. The possibility of using off-the-shelf hardware or surplus equipment should be investigated. Other similar testing programs in Germany and Japan may also be valuable sources of information on such equipment.

III. FACILITY REQUIREMENTS

The experimental support activities required for the development of the nuclear-process heat system may, at some point, involve the testing of complete components and subsystems. The magnitude of the heat loads and other operating conditions for such experimental units would seem to dictate the use of a reactor heat source and reactor helium. The design and evaluation of these large experiments will require the previous development of a base of expertise from experimental activities at the process equipment development level. Indeed, the equipment development experimental support program would itself be the product of other preliminary investigations and tests to develop the needed loop design data. The experimental support activities must therefore proceed in a stepwise manner in the overall program. The experiment described in the previous sections was utilized as a means of scoping the probable requirements at the equipment development testing level. It is evident that judicious design could produce an adequate experiment to test a complete module of a component in a recuperative loop with a rather modest electrical power input. This experiment and loop design represent a possible maximum capability that might be expected of the test facility for equipment development. All that follows is concerned with testing using electrical heaters.

The high-temperature helium test facility should be designed with the ultimate capability to accomplish module tests; however, the design must also provide for multiple smaller tests and loops with lower mass flow rates and lower input power requirements. In addition, the broad range of requirements, with respect to these parameters, anticipated for experiments dictates that for different experiments physically different hardware could be required since most loop components have relatively limited performance envelopes. The stepwise development of a full module test could include bench-scale tests for proof of concept, full-length tests for the proposed system component, and finally, the full-module test. These three testing regimes must be considered in the design of a facility for a comprehensive experimental program. The facility should incorporate sufficient square footage and ancillary support services to accommodate simultaneous activity in all three testing regimes. More specifically, this requires:

1. Multiple experiment test cells for bench-scale testing.
2. A high-bay experiment test cell for full-length testing.
3. A high-bay experiment test cell adequate for the module test.
4. Cranes and hoists for handling experimental units and loop equipment.
5. Electric power supply in the megawatt range.
6. A heat dump in this same range.
7. A data acquisition and process control system.
8. A machine shop.
9. An instrument shop.
10. Experimental unit preparation area.
11. Office and storage space.

It is anticipated that simultaneous operation of multiple bench-scale experiments will be required in the proposed experimental program. This mode of operation will require physical separation or scheduling in such a manner as to provide a safe environment for personnel involved in both setting up and operating the experiments. Experiments incorporating either continuous gas circulation (loop tests) or blow-down facilities are conceivable. Loop tests would require essentially all of the components shown in Fig. 4, whereas the blow-down tests might not require all these components but could require additional high-pressure storage and related gas handling components. Individual test cells or a larger laboratory area using blast fence protective separation could accommodate the experiments in this operation mode. These areas would require all the services associated with a high-bay test cell; however, the quantities of power, cooling capability, and flow capacity would be considerably less. At least one high-bay full-length process experiment test cell would be required. It would be desirable to conduct several experiments simultaneously in such a cell and it should be sized accordingly. These tests would most likely be of the loop configuration requiring components similar to those shown in Fig. 4. The high-bay module test cell should be located in close proximity to the full-length test cell so that a common service tower could be utilized. In view of this commonality the service tower will be described in more detail. At least one test cell sized for single experiments at the module level would be required. This cell could be expected to house all of the components illustrated in Fig. 4, possibly in the configuration shown in Fig. 5. It is desirable that the two high-bay test cells be designed so that personnel access to either cell can be independent of the status of operations in the other cell.

The common service tower should provide stairway and elevator access to the test cells at about ten foot level increments. Space should be provided for high-current bus bars in the event that it is desired to locate the heaters at the top of the test item. Gas, water, air, and electrical service would be provided to the cells from appropriate piping and wiring in this service tower. Instrumentation and process control cabling could also be routed through the service tower. The service tower and test cells could be an integral reinforced concrete unit providing isolation of the two cells, support for an overhead crane, and housing for common support services. The overhead crane should provide material and equipment handling capability for both test cells. Removable blast fence protection would be necessary for the access area of each cell in addition to a segmented folding door for protection from the elements.

Module testing at the level indicated for the reference experiment would require a power supply capable of furnishing 2.0-2.5 MW when the various losses are considered. The facility should have this capability in addition to, or in parallel with, the capability to run several smaller heaters at lower power. The power supply or supplies should be voltage- and current-controllable with

ramp-up and -down capability for startup and shutdown in order to minimize thermal shocking in the system, particularly in the furnace. Remote and programmed control of the power supply would also be desirable. Long-term testing will be required dictating that the power supply should have a relatively long mean time between failures.

Approximately 2 MW of cooling capacity (heat dump) are required for the reference experiment. For simultaneous operation of several loops (including the module test), additional capacity would be desirable. A heat dump is required for the loop conditioning heat exchanger, the bypass conditioning heat exchanger, cooling of the helium heater and any other components of the loop which require cooling. Previous graphite element heater designs have used water in the cooling system. This type of system would also be suitable for the heat exchangers and components requiring cooling. At least 5 MW of cooling capability should be provided.

The data acquisition and process control system will provide continuous monitoring of pressures, temperature, flow rates and other variables prescribed for particular tests. It should be capable of providing a permanent record of the appropriate variables in digitized format (magnetic tape); limited real time data reduction for real time display; interaction with the central computing system in order that data can be transmitted to that system for complete analysis and then returned to the data acquisition and process control system for hard copy output. In addition, there should be provision for process control including current in the heater, primary and secondary flow rate, and similar parameters in auxiliary equipment. Simultaneous operation of several test loops will eventually be required and the data acquisition and process control system should be capable of this type of operation. It is obvious that at the current stage of facility planning, all future test requirements are not known so that the system must be flexible and expandable to meet these future requirements. These data acquisition and control requirements could be met using a variety of available hardware; the approach presented here incorporates a minicomputer using real time operating software. A basic system is described in Fig. 12. The cost of this equipment is estimated at \$100,000 and is considered typical of most minicomputer based systems. There are

significant software advantages associated with the use of this type of equipment for the testing program proposed.

The facility requirements discussed herein are intended to serve as guidelines for a detailed design and cost study for the construction of a high-temperature helium test facility. They may also be applied to assess the capabilities and modifications required to adapt any appropriate existing facilities. A more detailed study of the experimental program is currently in progress.

Fig. 12.

Data acquisition and control system schematic.

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