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NATURAL CONVECTION AND HEAT ENGINE WORK

Final Report

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1.0 INTRODUCTION

This report endeavors to summarize a portion of the work which has been accomplished under the contract between the Chrysler Corporation and the University of Michigan, concerning nuclear engineering research and development, along two broad lines of investigation. These are:

1. The investigation of nuclear-powered heat engine parameters with special reference to those systems which seem adapted to automotive applications by virtue of low weight and size capability coupled with economic operation.

2. The investigation of heat transfer behavior of fluids of interest as homogeneous nuclear reactor heat extractants and fissionable material solutes, including both liquid metals and aqueous fluids.

1.1 Nuclear-Powered Heat Engine Parameter Investigations

If light-weight, small-size, economic, automotive-type nuclear power-plants are to become a practical reality, it is necessary that intensive investigations of all conceivable heat engine cycles in conjunction with suitable nuclear reactors be conducted. Preliminary studies of this type, by the present group, disclosed several arrangements which appeared to possess special merit and be worthy of further consideration. Chief among these was the closed-cycle, high-pressure gas turbine plant. As a result, along with general studies of other types of plants, more detailed studies of the various components constituting a closed-cycle gas turbine system were made. A summarization and the references to the detailed work are given in this report.

1.2 Heat Transfer with Homogeneous Reactor Fluids

A reactor type which appears to possess real potential for automotive applications is the cartridge type of high temperature molten metal-fueled reactor, consisting of a critical configuration into which is incorporated the heat transfer surface for extracting the heat of fission. The process of heat transfer in this case includes forced convection of the coolant side, thermal conduction through the wall separating coolant and molten metal, and natural convective heat transfer from the fissionable material solute to the separating wall. With the state of present knowledge, the natural convective heat transfer, from a fluid containing a volumetric heat source, is, of the three heat transfer processes which are involved, the least defined. However, it appears to represent a controlling parameter in many cases for maximum power production and hence minimum weight for minimum size of a nuclear reactor of this type. It also appears to affect significantly the distribution of wall heat flux, the temperature distribution, hence the nuclear flux distribution, the process of entrainment and disentrainment of fission gases, the possibility of mass transport and/or erosion from the natural convective velocities on the tube walls.

In order to obtain data to allow the realistic design of reactors of this type, a program of analytical and experimental research into this area was initiated. The results are summarized in this report and the sources of the more detailed work referenced.

2.0 HEAT TRANSFER INVESTIGATIONS AND ANALYSES

2.1 Purpose and Motivation of Investigations

Perhaps the primary objective of the overall nuclear engineering contract between the Chrysler Corporation and the University of Michigan was the evaluation of the feasibility of some form of light-weight, high-performance, compact reactor powerplant. In many cases, the limiting factor to the success of such a plant will be the heat removal capability. Also, a large portion of the more promising arrangements involve the use of liquid metals as primary and/or secondary coolants for the transport of the fission heat from the reactor to the heat engine working fluid. Consequently, it seemed most desirable to investigate thoroughly the heat transfer and heat transport capabilities of the various liquid metals which are of interest in this context.

2.2 Liquid Metal Properties, Heat Transfer Relations, and State of the Art Investigations

A survey of all applicable liquid metal properties, heat transfer relations for both forced and free convection, and the state of the art for the prediction of heat transfer coefficients at the present time was completed and is reported in detail in Reference 10 and summarized in Reference 7. This study includes the derivations of the relations between pumping work and heat transfer and/or heat transport for heat exchangers, a set of nomographs for the calculation of heat transfer coefficients for various applicable liquid metals, and a review of the discrepancies between present theory and test results. These appear to involve in many cases inadequate control of gas entrainment.

2.3 Natural Convection Analytical and Experimental Program

A reactor type which appears to possess real potential for several automotive applications is the cartridge type of high temperature molten metal-fueled reactor. Such a reactor consists of a critical configuration into which is incorporated the heat transfer surface for extracting the heat of fission. The process of heat transfer in this case includes forced convection on the coolant side, thermal conduction through the wall separating coolant and molten metal, and natural convection and conduction from the fissionable material solute to the separating wall. At the present time, the natural convective heat transfer from a fluid containing a volumetric heat source is, of the three heat transfer processes involved, the least well defined. However, in many cases it represents a controlling parameter for maximum power and minimum weight. It also involves a permutation of the nuclear flux (through the temperature influence) of the tube wall heat flux and, hence, of the thermal stress problem and of the tube wall temperature. All of these will be varied in many cases substantially from those calculated by assuming as a first approximation that the heat transfer from the liquid metal is by pure conduction.

To obtain data to allow the realistic design of reactors of this type, a program of analytical and experimental research into this area was initiated.

Although the basic objective of the program was the attainment of an understanding of the natural convection heat and mass transfer phenomenon with liquid metals, it was decided as a first step that experiments with aqueous solutions should be conducted. It was felt that in many ways the phenomenon with aqueous fluids would approximate in nature that with liquid metals. Since visualization of the flow behavior is possibl with water although not with liquid metal and since the instrumentation and container problems are greatly relaxed, it was felt that a great dea could be accomplished in this manner toward a basic knowledge of the nature of the phenomenon.

The type of facility to be employed with either aqueous solutions or liquid metals is identical. It was decided that the heat should be generated internal to the fluid to approximate the case of a constant nuclear flux in a homogeneous liquid-metal-fueled reactor. Since the end effects of any practical vessel are of importance, it was decided that vertical closed-end tubular test sections should be used with only moderate ratios of length to diameter. The heat was to be removed by an external coolant jacket. It was decided that the most practical method of generating heat under these conditions would be through the use of the ohmic resistance to the passage of electrical current of the test fluid itself. This is a relatively simple matter with aqueous solutions since the electrical conductivity can be adjusted to the approximate value desired by addition of electrolyte. With liquid metals, however, the electrical conductivity is inconveniently high so that a source capable of providing very high currents at very low voltage is necessary.

In addition to the investigation of liquid metal heat transfer, facilities of this sort could also be used to determine

1. The effect of agitation produced either mechanically or electromagnetically on natural convection heat transfer. It appears likely that a large scale increase in heat transfer may be effected by a modest expenditure of electrical energy.

2. Effect of "wetting" and/or gaseous entrainment on heat transfer. Substantial quantities of gas may be expected to be present because of the release of fission product gases. Also, gaseous entrainment may be a necessary consequence of many of the proposed designs of mechanical pumps.

3. Erosion and/or cavitation effects in high temperature liquid metal systems

2.3.1 General Description of Research Facilities

In accordance with the experimental program outlined in References 11 and 12, facilities capable of utilization with aqueous fluids, mercury, and eventually high-temperature molten metals of interest have been designed. The actual experimental program was commenced with aqueous solutions. However, it was expected to proceed to mercury and eventually to high-temperature bismuth or lead bismuth. The layout drawings of the facilities are included in Reference 7 as well as preliminary photographs. It might be mentioned that there are two aqueous facilities: a larger facility which is water-cooled and is shown in the previously mentioned layout drawing, and a smaller facility which is air-cooled. A photograph of a preliminary version of the air-cooled facility is shown in Reference 7. Figure 1 of this report is the present air-cooled facility. The installed and modified water-cooled facility is shown in Figure 2, and the completed mercury facility (exploded and assembled views) in Figures 3 and 4. A complete explanation of the design philosophy and a detailed description of each facility is incuded in Reference 7. In addition to the equipment mentioned above, a low-voltage, high-current transformer bank with suitable instrumentation has been procured for the mercury facility.

Analytical and design efforts were conducted to specify those modifications to the mercury facility which would be necessary to allow the use of high-temperature molten metals. Principally these involved replacing the boiling-water cooling system with a forced-draft air system. It was determined that an annulus adjacent to the test section should be provided for the cooling air, and a second larger annulus, outside the primary cooling passage but still within the brass outer container (which serves as an electrical conductor). Thus, an intermediate tube, between the test section and the brass container would be required. This would prevent to a large extent radiation heating of the brass conductor, while a small portion of the air, passing through the outer annulus, would remove the ohmic resistance heat from the brass container. This is necessary to maintain a reasonably low temperature in this component which will prevent excessive electrical resistance losses. The detailed description of the required modifications is given in Reference 13. Also included in this reference is the preliminary specification and costing of the auxiliary equipment and instrumentation required.

2.3.2 Experimental Program - Natural Convection

The experimental work in natural convection has been confined to the aqueous facilities, since delivery from the shops of the mercury facility was obtained only in the closing weeks of the

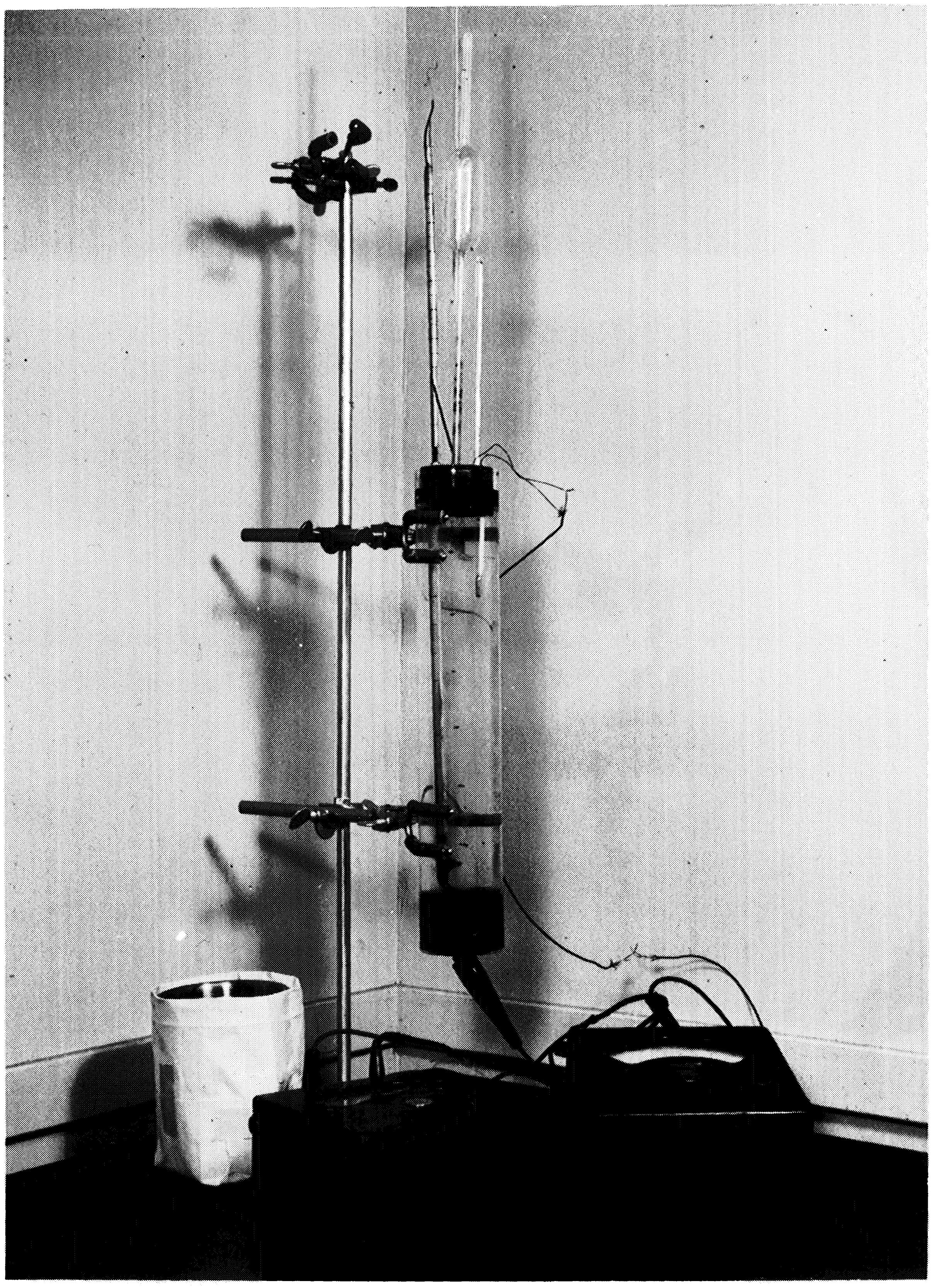

Fig. 1. Photograph of Air-Cooled Aqueous Facility

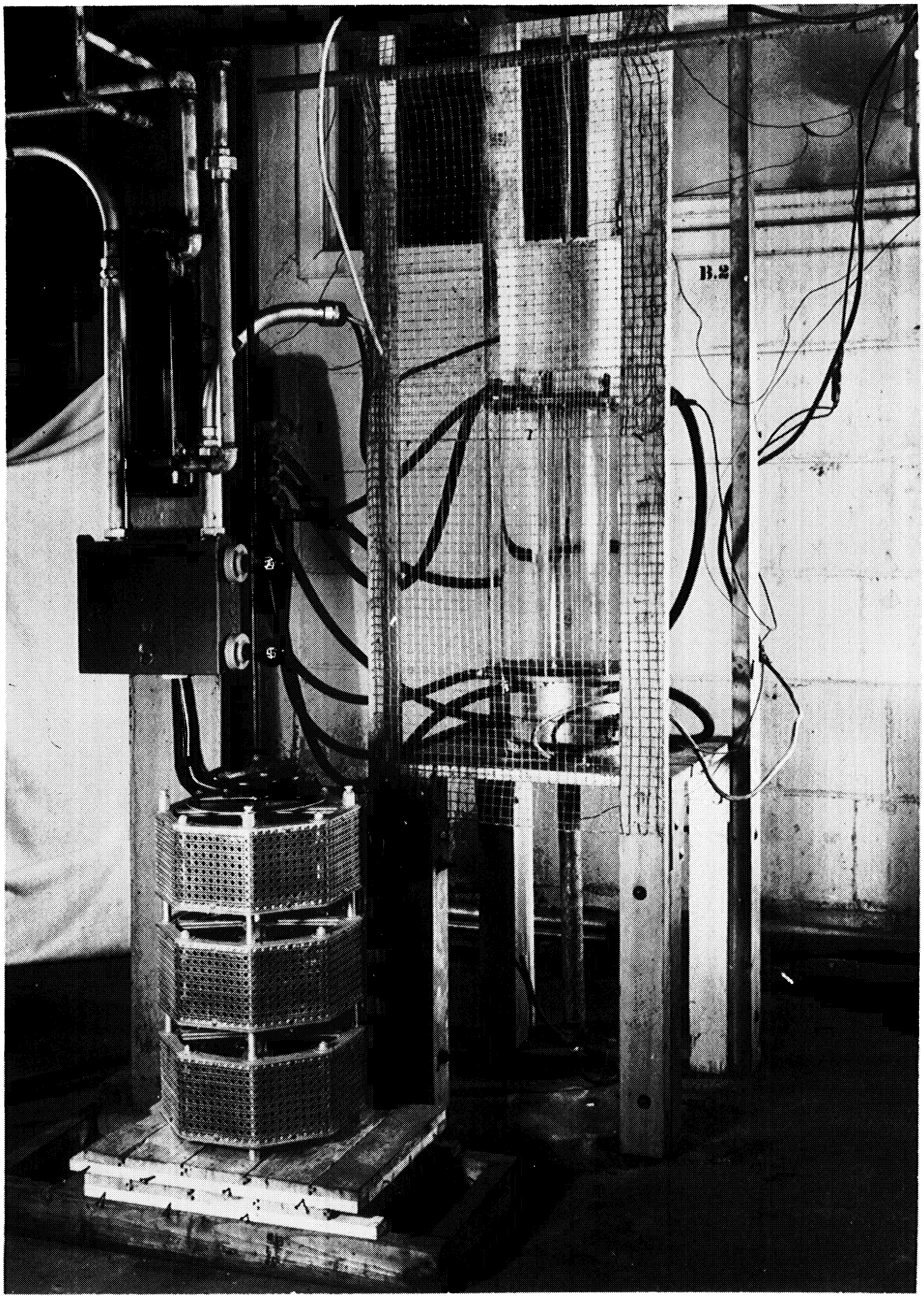

Fig. 2. Photograph of Water-Cooled Aqueous Facility

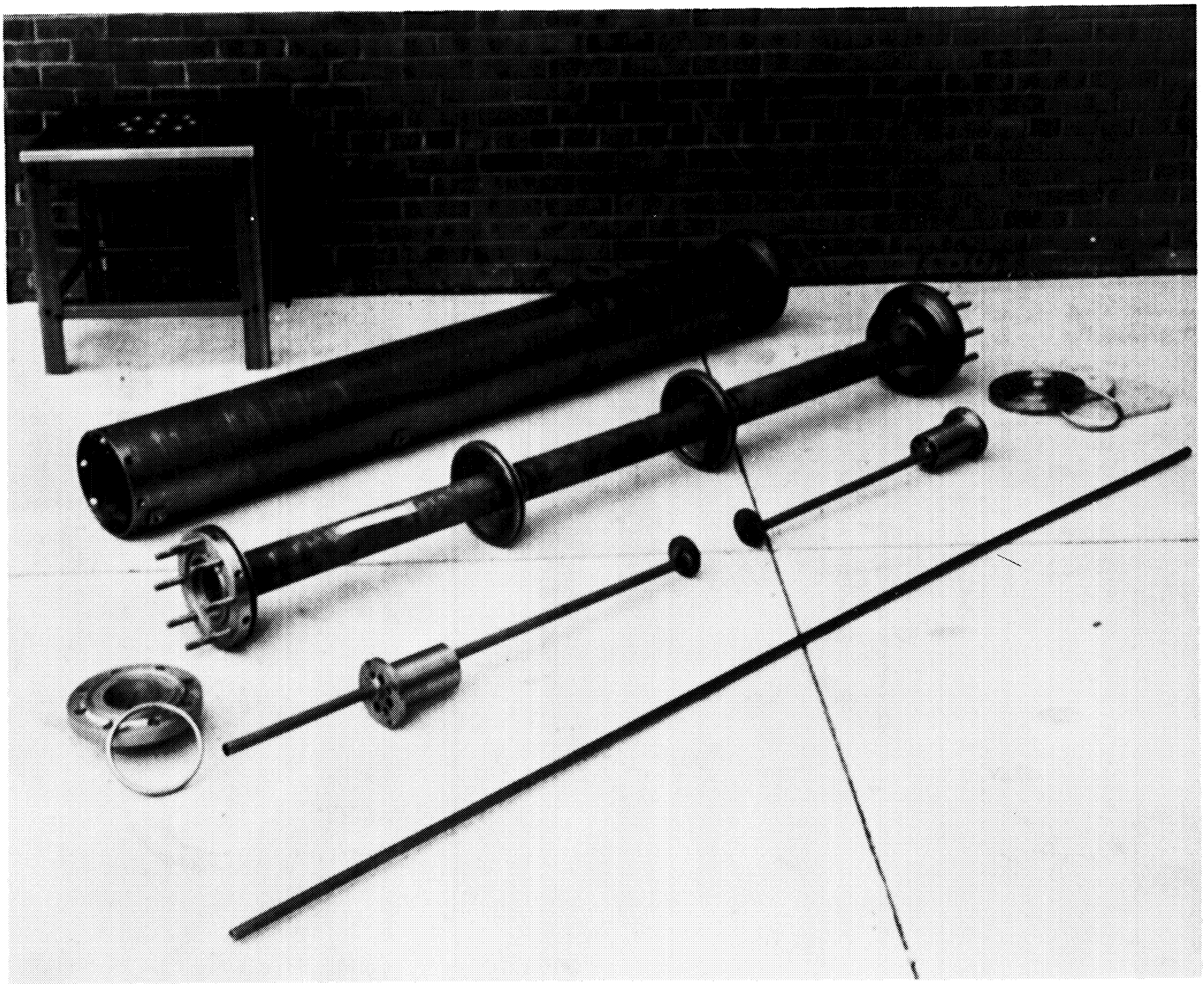

Fig. 3. Photograph of Liquid Metal Facility (Exploded View)

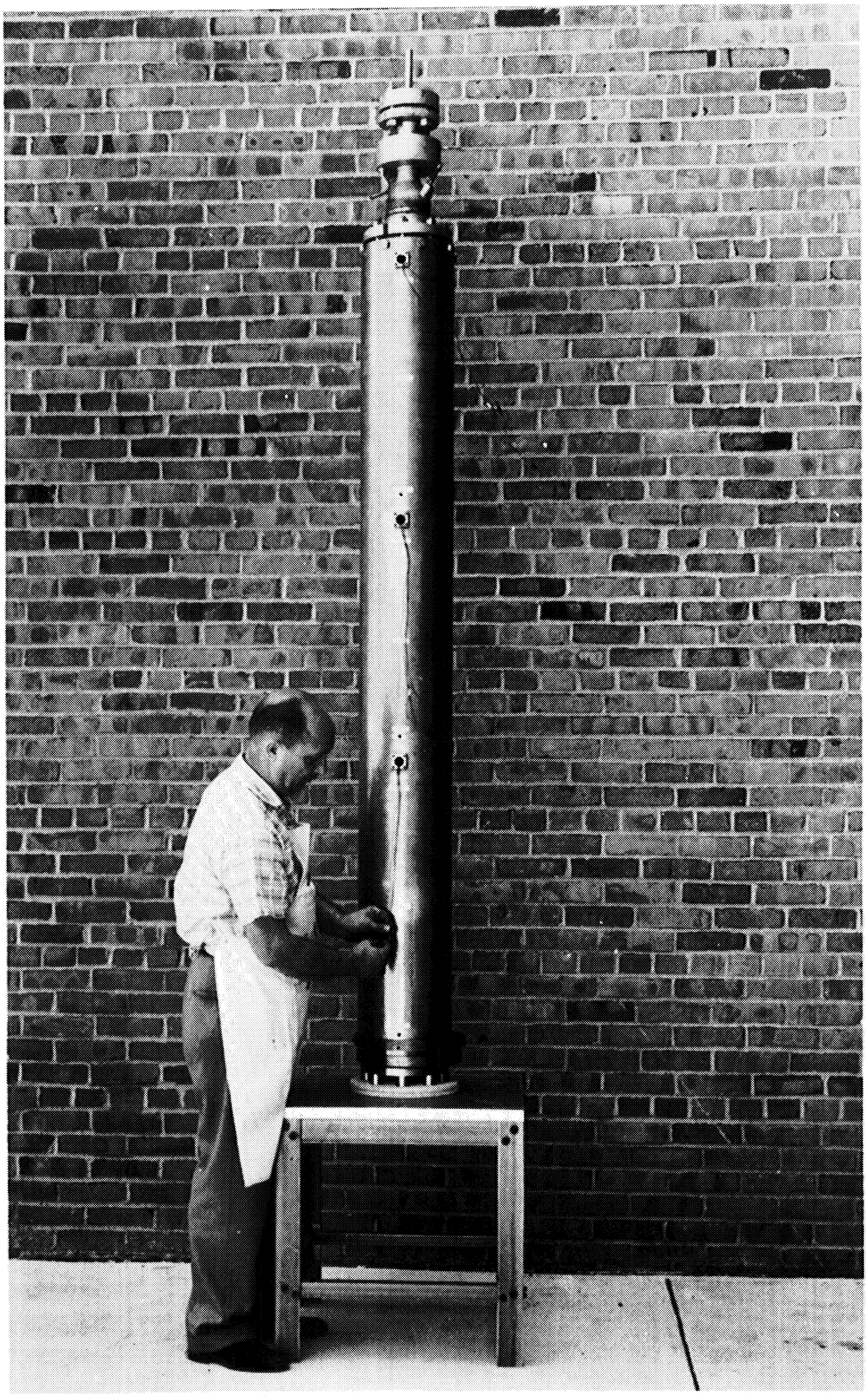

Fig. 4. Photograph of Liquid Metal Facility (Assembled View)

contract. Due to the termination of the contract, the experimental work was not sufficient to allow definitive conclusions to be reached. However, the preliminary runs with the water-cooled facility did indicate that a satisfactory heat balance existed between the electrical input and the heat removed with the cooling water. It was thus established that no unknown chemical reaction was absorbing significant quantities of heat.

The detailed analytical and experimental work will eventually appear in the present writer's doctoral thesis and will thus become available to the Chrysler Corporation. A description of the preliminary results is included in Reference 7.

2.3.3 Experimental Results - Electrical Film Resistance

If there were an appreciable contact electrical resistance between the steel electrodes and the fluid, the assumption of a uniform volumetric heat flux in the fluid would not be applicable. Consequently, tests to determine the magnitude of such a resistance for the aqueous electrolyte, for mercury, and for lead-bismuth eutectic were conducted.

The preliminary tests (Reference 14) showed that the resistance for the aqueous solutions and for mercury were too low to be of significance in the various facilities. This has since been confirmed by actual voltage measurements in the aqueous facility. The results are summarized further in Reference 7. However, the instrumentation and methods used were crude and it was decided to attempt to obtain more definitive data for mercury and also for lead-bismuth eutectic. Aside from the present context, such information would be of great value in predicting the performance of electromagnetic pumps or meters with bismuth.

The second group of experiments, using a more refined technique, is described in Reference 15. As a result of these experiments, it appears that the film resistance between the electrodes and the mercury is not significant because of the large surface area exposed by the electrodes. However, the resistance between the mercury and the flat-plate baffles which conclude the test section at either end does appear possibly significant. As a result, these have been serrated to maximize the surface area. Actual tests within the mercury facility may have shown that a plating with perhaps silver or copper of these components may have been necessary to reduce further this electrical resistance. It also appeared that the cleanliness of the mercury and the surface (stainless steel) is very important. Perhaps adequate cleaning procedure and/or a preliminary soaking to promote wetting would be adequate. The results of the lead-bismuth test appear to indicate a somewhat higher surface resistance than with mercury. However, it is believed that suitable cleansing of the surfaces, prevention of oxidation, and long-duration soaking may appreciably reduce the initial resistance. It has been reported by Brookhaven that a lengthy soaking period appeared necessary to allow proper performance of their electromagnetic pumps in bismuth loops. A similar experience has been encountered in the work on this project at Willow Run.

2.3.4 Experimental Program - Velocity Instrumentation

The determination of fluid velocity for the aqueous tests has been successfully accomplished by injecting Nigrosin dye at known locations and timing the motion. However, the problem is much more difficult with liquid metals.

Preliminary calculations had indicated that velocities in the mercury facility large enough to be measured with a Pitot-static tube combination would exist, if these could be converted into a head of water or other light fluid. A gas-injection manometer system was devised for this purpose. Bench models were fabricated and tested. It was found that the bubbling mechanism would be successful in water, but due to uncertain wetting conditions, success was not attained with mercury. Tests with lead-bismuth were not conducted.

The test program and the results are described in Reference 16 and summarized in Reference 7. This phase of the work was discontinued because an alternative approach appeared more fruitful. However, it is believed that the instrument as developed would be a useful tool for the measurement of velocities in streams of fluid which cannot conveniently be removed to a manometer due to toxicity, temperature, etc. It was shown to be successful for fluids which wet the material of the probe. Thus, it is presumed that the general principles would also be adequate for liquid metals if proper probe materials or surface treatments were found.

The bubbling Pitot tube concept was replaced by the concept of micro-Pitot tubes. An instrument was constructed. It is pictured and described in some detail in Reference 7. Tests were conducted and it was found that a mercury level could be reproducibly located to plus or minus approximately 0.001 inches. No tests with lead-bismuth eutectic or other liquid metals were made. With the above accuracy it would have been possible, according to the preliminary calculations, to measure with a fair degree of accuracy the mercury velocities.

2.3.5 Experimental Program - Electrolyte Conductivity

Sodium-acetate was chosen as the electrolyte for the aqueous tests because of its non-corrosive properties with the carbon steel equipment. It was then necessary to evaluate the physical properties of the fluid. Because of the uncertain influence of the Ann Arbor tap water, the electrical conductivity of the fluid as a function of temperature and normality was evaluated experimentally. This, and the other applicable physical properties, are reported in detail in Reference 17.

2.3.6 Analytical Investigations

Considerable progress in the analysis of the natural convection flow phenomenon has been achieved. Initially, a thorough review of the literature was made so that a good understanding of the present state of the art was developed. In general, it was found that virtually no analytical or experimental studies have covered the case of a vessel of moderate length to diameter ratio wherein the heat is generated within the fluid as in a homogeneous nuclear reactor. Most past studies have dealt with a flat plate geometry, usually in an infinite sea of fluid. The present case is specialized beyond the existing literature in at least three ways:

1. Vessel is closed at both ends and is sufficiently short so that end effects are significant.

2. Heat is generated within the fluid in various non-uniform distributions. Also wall temperature distribution is arbitrary.

3. Fluids of greatest interest are liquid metals. These differ very significantly from aqueous fluids in that the Prandtl number is of the order of 0.001 to 0.01 rather than 1.0.

There are some experimental and analytical studies of natural convection in liquid metals to be found in the literature, but they do not cover the applicable geometry and/or method of heat generation. Also, there are some studies of internal heat generation although not for the applicable geometry, boundary conditions, or fluid. Due to the lack of a general understanding and solution for natural convection heat and mass flow problems it is very difficult to apply experimental or analytical work to cases far removed from that actually under study.

The closest approach in the existing literature to the cases of present interest is the work of Lighthill (Reference 18). In this paper an investigation of a tube closed at one end but open to an infinite reservoir at the other of a temperature different from the wall temperature which is uniform is made. The method employed is the assumption of velocity and temperature profiles which meet the boundary conditions up to and including the first derivative, and the integration for all cross-sections of mass, momentum, and energy. Thus, the balance of these quantities is not necessarily satisfied for a point to point basis.

This general method was adapted to the present case and generalized to include closure of the vessel at each end, an internal heat source of arbitrary axial distribution, and an arbitrary axial distribution of wall temperature. The method of solution is a double iteration. This has been programmed for the IBM-650 digital computer and a network of curves covering the various combinations of parameters of interest was to have been run. Some of the preliminary results are listed, and a more detailed description of the method, the expected results, and the anticipated work given in Reference 19. A more preliminary description of the method for aqueous fluids is given in Reference 20. Some of the preliminary expectations for the effects with liquid metals rather than aqueous fluids and for the behavior of experimental facility of the type previously described are given in Reference 21.

3.0 HEAT ENGINE ANALYSES

3.1 General Problem

The attainment of a practical light-weight, small-size nuclear powerplant capable of economic operation appeared to involve the selection of a heat engine system arrangement most suited to the particular application. Consequently, a broad investigation of the various conceivable heat engine systems with particular emphasis on their integration into a nuclear powerplant design seemed warranted. Analytical studies along this general line have been in progress for the duration of the contract. The results of the work have been detailed in past reports, References 1, 2, 3, 4, 5, and 6.

3.2 Critical Review of Various Types of Heat Engine Systems

A critical review of the various conceivable types of heat engine systems which appeared applicable was conducted. These included:

1. Steam plants
2. Gas turbine systems
3. Binary or trinary vapor systems

The results of these studies are reported in detail in Reference 2 and summarized briefly in Reference 7.

3.3 Gas Turbine Systems

3.3.1 Initial Studies

Because of their apparent light-weight and small-size capabilities, the gas turbine systems were given special attention. Open cycles and also closed cycles operating at a high pressure level with air and also other fluids were considered. Various cycle arrangements were investigated. The initial analyses are reported in detail in Reference 2 and summarized briefly in Reference 7. In general, they were as follows:

1. Thermal efficiency evaluations considering various working fluids, temperatures, pressure ratios, cycle arrangements and component efficiencies.

2. Thermal efficiency evaluations, considering a selected cycle arrangement, and developing the economically optimum attainable component efficiencies under the peculiar conditions of a nuclear powerplant, for each of the principal components, for various conditions of pressure, temperature, power level, and fluid selection.

As previously stated, the initial results, performance curves, etc. are given in detail in Reference 2. In this initial phase, the fluids investigated were helium and air (it may be assumed that the air results may be applied to nitrogen also with little error). At a later date, the investigation was broadened to include carbon-dioxide (Reference 3). It was found that the attainable thermal efficiencies for given temperature levels did not depend strongly on the gas although, with equal component efficiencies, there was some slight advantage to the diatomic or polyatomic gases over the monatomic (efficiency increased with a decrease in the ratio of specific heats). It was also determined that the optimum pressure ratio decreased with an increase in k. A typical value for helium is about 2.3 while a corresponding value for air is 3.0.

A comparison between the gas turbine and the Rankine-type cycles (steam or binary-vapor) showed that for maximum cycle temperatures below 1100-1200°F, the thermal efficiency attainable with Rankine-type was considerably in excess of that attainable with gas turbine plants. Above this range of temperature the steam system appears to hold an efficiency advantage up to at least 1500°F, although the difference at this point is small. The binary (or trinary) vapor cycles maintain the advantages of a saturated Rankine cycle into the high temperature region. Thus, they offer an efficiency which is the equivalent of the steam cycle at low temperature, but a considerably greater efficiency at high temperature.

3.3.2 Gas Turbine Component Optimizations

As a result of the previously mentioned preliminary studies, it was decided that a closed cycle with highly effective regenerator and the reduced pressure ratio which this dictates would be most appropriate for a nuclear-powered plant designed for small size and high performance. Consequently, efforts were directed toward the economic optimization of the various components which constitute such a plant. The components which were considered are:

1. Turbomachinery components
2. Gas turbine cycle heat exchangers
3. Nuclear reactor

The work considering each component is summarized below.

1. Turbomachinery Components

   A study of the turbomachinery components was completed to provide an estimation of the efficiencies which could be realistically anticipated from these components under varying conditions of working fluid, power level, pressure level, and temperature. Optimum blading loss coefficients, considering conventional design practice with respect to Mach numbers and pressure ratio per stage, were evaluated. The effect of machine size and Reynold's number as it is affected by the choice of fluid was considered. Calculations were made for air and helium (Reference 2) and for carbon-dioxide (Reference 3). The resulting efficiencies were applied to a cycle which included arbitrary (and constant) assumptions regarding friction pressure ratios and regenerator effectiveness. The results were corrected to the optimum pressure ratio for each fluid and are presented in Reference 3. Under these conditions, helium appears at a thermal efficiency disadvantage to air or carbon-dioxide, which are approximately equal in this respect. Also, low pressure level cycles show an efficiency advantage over higher pressures because of the higher efficiency of larger turbomachines. These results are also summarized to some extent in References 7 and 8.

2. Heat Exchanger Components

An examination of the various heat exchanger components which are included in a closed-cycle gas turbine powerplant shows that the regenerator and the heat source exchanger are by far the most expensive and critical to the success of the overall design. Consequently, a detailed examination of these particular components was conducted resulting in economic optimizations with particular reference to nuclear powerplants and including the cost of nuclear fuel.

Regenerator Component

An economic optimization for the regenerator component in a nuclear-powered closed-cycle gas turbine plant was completed (Reference 3). The calculations considered both air and helium although carbon-dioxide was not included since it was believed that the results would be close to the results for air. A specific type of heat exchanger which it was felt was typical of the most applicable type was used. This was the "all-prime surface" design manufactured by the Griscom-Russell Company and providing passages of 1/16th inch diameter. The small passages are permissible since the gas remains clean in a nuclear plant.

As a result of this work, it is possible to select the economically justified design for plants covering a range of output (600-60,000 h.p.), maximum cycle temperature (1500-900°F), and maximum cycle pressure (1000 to 45 psia) for either air or helium. Considering the type of surface assumed, the overall dimensions, number of passages, friction pressure ratio, fluid velocities, and Reynold's number are presented. It was shown that the optimum effectiveness ranges from about 0.92 for the maximum pressure to about 0.56 for the minimum. These results apply for air. The helium results do not vary so greatly but follow the same trend. It was also shown that the economically optimum velocities, Reynold's numbers, and frictional losses are much smaller than had been previously anticipated.

The resulting effectiveness values were applied to the overall plant thermal efficiencies, using the optimum turbomachinery efficiencies previously established. As before, there is an advantage in efficiency to the air cycles. However, because of the substantial drop in regenerator effectiveness with pressure, the advantage of the low pressure cycles is nullified and reversed in some cases. These results are summarized in Reference 7 and reported in detail in Reference 3.

Reactor Component

An economic optimization for the reactor component in a nuclear gas turbine powerplant has also been completed and is reported in detail in Reference 5. The objective of the study was more to discover trends and orders of magnitude rather than specific design values. In order to limit the scope of the work to a feasible effort, a single specific type of reactor was assumed. This was of the liquid-metal-fueled type, containing a solution or slurry of uranium in bismuth contained in discrete "wells" in a graphite block which also serves as moderator. Gas coolant was assumed to be conducted through parallel passages in the block suitably lined in some manner to contain high pressure gas. The gas coolant is also the working fluid for a closed-cycle gas turbine system. This type of reactor was selected as being somewhat typical of those which seem most suitable for light-weight, economically competitive, high-performance reactor systems.

A preliminary study of this type was reported in Reference 6. Reference 5 is a more careful re-evaluation of the system, and present economically justified pressure drops, film coefficients on the gas side, velocities and Reynold's numbers, the core diameter, and corresponding critical mass. For the type of reactor assumed, it was found that for relatively small outputs (up to, say, 5000 SHP) the optimum designs were characterized by low film coefficients and gas velocities since the reactor size was controlled by the cost of uranium inventory rather than heat transfer area. The critical mass requirement increased rapidly as the core diameter was decreased beyond perhaps 3 feet. Hence, the reactor core was oversized from the viewpoint of heat transfer area. For larger power outputs in the order of 20,000 SHP, the reactor heat transfer and heat transport areas become controlling, so that the film coefficients, velocities, Reynold's numbers, and pressure loss ratios are greatly increased. For still larger outputs, the burn-up cost becomes controlling so that the loss in thermal efficiency occasioned by large pressure and temperature drops in the reactor can no longer be tolerated. In these cases, the optimum core diameter is increased and the gas side heat transfer performance reduced.

The calculations considered a reactor temperature limitation of 1700°F on the gas side tube wall, gas pressures ranging up to 1000 psia, but only air as working fluid. It had been intended eventually to consider helium also so that a comparison between air and helium would have been afforded. This has not been accomplished to date.

3. Present State of Gas Turbine Optimization Studies

To the present, considerable data regarding the optimization of the various components which together constitute a closed-cycle nuclear-powered gas turbine system have been accumulated. To organize this work into meaningful overall results, it is believed that the following additional steps would be necessary:

Completion of reactor heat transfer optimization studies considering also helium and perhaps carbon-dioxide

Integration of the various optimized components into a complete plant so that the effects on optimized thermal efficiency of pressure level, temperature level, and fluid choice could be ascertained.

Cost estimations for overall plants so that overall economic optimum designs could be determined comparing the effects of pressure, temperature, and fluid choice. It is reasonable to suppose that the economically optimum plant design will not correspond to the maximum thermal efficiency design.

Additional useful work in this general direction would include optimization with respect to weight rather than cost and an attempt to determine how serious would be the effect on cost if a movement in the direction of the minimum weight design were made. Also, a cost and weight comparison for various temperatures and sizes between the optimum gas turbine designs and optimum Rankine cycle plants would be useful. A preliminary attempt at this is presented in Reference 6.

3.3.3 Gas Turbine Pilot Plant Investigation

Since the analytical investigations discussed in the foregoing sections appeared to show the desirability for a light-weight, compact nuclear powerplant of a closed-cycle gas turbine system, it seemed desirable to consider the possibility of a research facility to investigate those many aspects of a closed-cycle plant to which physical research and development might usefully be applied. At the present time, no actual experience with units utilizing fluids other than air exists. There has been, over the past decade, developmental work on closed-cycle, oil-fired units in Europe. However, even this limited experience with air units has not been shared by companies in this country.

For these reasons, the construction of a pilot plant facility, capable of closed-cycle operation with various gases of interest at various pressure and temperature levels was investigated. Such a unit would allow the obtaining of actual operating experience with gases other than air at various pressure and temperature levels in a fully integrated closed-cycle system. Those aspects of the overall problem to be evaluated in this manner would include the actual performance of heat exchanger and turbomachinery components for gases with which very little operating experience is presently available, the problem of providing a suitable sealing system for the working fluid at high temperature and pressure, high temperature container and corrosion problems, system control problems, and those numerous other problems whose present existence is unsuspected and can be uncovered only by physical research. Also, a working unit not too far removed from a prototype of a small output plant would be provided, and invaluable training of personnel afforded. At the conclusion of a physical research program of this sort, a realistic appraisal of the future potential and present cost of plants of this type would be possible.

A preliminary study of such a pilot plant facility was completed and is reported in Reference 4 and summarized in Reference 7. It was shown that a facility capable of self-sustaining closed-cycle operation with gases ranging in molecular weight from helium to carbon-dioxide over a limited pressure range and at temperatures up to about 1300°F could be constructed with commercial turbo-supercharger units. The heater would be an oil or gas-fired closed unit which is also commercially available.

3.4 Additional Heat Engine Studies

In addition to the various gas turbine system studies and the comparative studies between steam, binary-vapor and gas turbine systems, several additional, more minor, heat engine investigations were also conducted. These included the following:

1. Thermodynamic studies of binary and trinary vapor systems using sodium as the high temperature fluid exchanging heat with (a) steam system, (b) mercury-steam system, and (c) gas turbine systems. These investigations are reported in detail in Reference 2 and summarized in Reference 7. An additional, more detailed analysis of the thermodynamics of the sodium cycle considering the effects of the dimerization of the vapor are reported in Reference 3. In addition (same reference), a typical sodium turbine design was carried through.

2. Thermodynamic studies of vapor-gas mixture cycles (Reference 3). The work included an evaluation of the effect of the addition of water vapor to the working fluid of a closed-cycle gas turbine system (no substantial improvement in efficiency resulted), and also an analysis of a regenerative air-water cycle in which water would be injected and vaporized in the high pressure portion of the regenerator and also in the heat source, and condensed and removed in the low pressure side of the regenerator and the heat sink (Reference 3). It was shown that the resulting cycle was comparable to the gas turbine cycle in thermal efficiency if the waste heat were utilized by a low temperature steam cycle. It is not as dependent as a gas turbine system on good compressor performance (since the proportionate compressor work is reduced), and, hence, might show improved stability and off-design performance. However, the additional complexity and the probable equipment cost appear great.

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