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GAS-COOLED REACTORS IN THE USA

A SURVEY AND RECOMMENDATION

by

R. H. Armstrong

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Reactor Engineering Division

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I. Introduction

This survey was undertaken for two reasons. The first was to provide an understanding of the status of gas-cooled reactors as used for unclassified applications. The second was to determine phases of advanced research and development needed in the field and from these to recommend a program for high-temperature, gas-cooled reactors. The documents used in this survey were limited to those investigations performed in the last five years.

However, so much of the basic data pertaining to gas-reactor development originated with the Daniels Pile Group at Oak Ridge National Laboratory that reference is made to report MON-N-383.(93) Supporting research for this project was carried on at Argonne National Laboratory, Battelle Memorial Institute, Westinghouse Electric Company, Norton Company, and others. This research has provided a basis for establishing the practicability of the gas reactor concept. Those now engaged in gas reactor development may be interested in reviewing this report.

Although this survey is on gas-cooled reactors in the USA, for purposes of comparison the tabulation in Fig. 1A, Columns A and B, lists the Calder Hall and Hinkley Point British reactors. In addition, to illustrate some advanced British concepts, Fig. 1C, Columns AN and AR, lists the British steam-cooled pressure tube reactor and the "Dragon" project.

Since this is a historical survey, the majority of the subject matter was obtained from the references. The observations and recommendations, however, are the author's opinions.

II. Summary

A study of some 132 reports on gas-cooled reactors and related subjects has been made. These, and an additional 37 reports of a classified nature, are listed in the bibliography. Fig. 1 lists the representative group of reactor types under discussion. Some of the reports investigated represent duplicate effort; therefore, the tabulation lists what the author believes to be the most representative.

Among the reports investigated are several by General Electric Company,[64-66] General Atomics,[39-47] and Oak Ridge National Laboratory.[111-120] These reports are thorough and well done, and cover the selection of gas coolants, gas cycles, and materials for use in a high-temperature gas environment. For the most part, these reports describe reactors for use up to a maximum gas outlet temperature of 1300°F. From all the reports studied, a number of charts and tables have been duplicated and are incorporated in Section VI; these are briefly described as follows:

Figures 1A, B, and C consists of three tables which list all available reactor information.

Figures 2A, B, and C are reactor flow diagrams of suggested concepts.

Figure 3 shows a possible fuel arrangement at the core cross section.

Figure 4 shows a typical fuel and moderator cell.

Figure 5 shows possible fuel types for the unit fuel cell.

Figure 6 tabulates the properties of materials for moderators and reflectors.

Figure 7 - Table 1, outlines the compatibility of gases and bare fuel materials at maximum surface temperatures. Table 2 outlines the maximum interface temperatures of fuel elements and core-jacket combinations. Table 3 tabulates the allowable operating temperatures and compatibility of gases and various metals. Table 4 lists the preferences for gas coolants. Table 5 lists the cost and availability of gases. Table 6 shows in graphical form plant thermal efficiencies versus maximum cycle temperature for three gases.

Figure 8 - Table 7 lists the thermal properties of three gases. Table 8 shows in graph form a comparison of related pumping power versus reactor coolant inlet temperatures. Table 9 lists obtainable heat fluxes.

Figure 9 - Table 10 tabulates composition and physical properties of some potential cladding materials. Table 11 lists the atomic and thermal properties of some potential cladding materials. Table 12 lists fabrication characteristics, availability, and costs of some potential cladding materials.

Figure 10 lists possible process applications of gases at high temperature.

Figure 11 tabulates potential high-temperature materials (from Metal Working Magazine).[168]

During the past five years, many studies have been made on various types of gas-cooled reactor systems, which are divided into the following catagories and which are tabulated in Fig. 1:

				Columns
1.	Graphite Moderator and Reflector			
	a.	Indirect closed cycle	heterogeneous fuel	C,D,E,AV, AM,AO
	b.	Direct closed cycle	heterogeneous fuel	G,M,U,V, AB,AC,AE, AF,AG,AK.
	c.	Indirect open cycle	heterogeneous fuel	O
	d.	Indirect closed cycle	fuel in liquid metal	AL
	e.	Indirect closed cycle	fuel in moderator	AD
	f.	Indirect closed cycle	particulate fuel	L,P,AA
2.	D_2O Moderator and Reflector			
	a.	Indirect closed cycle - pressure tube	heterogeneous fuel	K,R
3.	Zirconium Hydride Moderator and Reflector			
	a.	Direct closed cycle	heterogeneous fuel	H
4.	H_2O Moderator and Reflector			
	a.	Direct closed cycle	heterogeneous fuel	J,W,AH
5.	D_2O Moderator and H_2O Reflector			
	a.	Indirect closed cycle - pressure tube	heterogeneous fuel	S,T,AN
6.	H_2O Moderator and BeO Reflector			
	a.	Steam-cooled - direct cycle	heterogeneous fuel	AP
7.	BeO Moderator and Reflector			
	a.	Direct closed cycle	heterogeneous fuel	F

The foregoing reactor types are tabulated in Figs 1A, B and C.

Three of these proposals are authorized for construction (see Fig. 1): the Kaiser-AC experimental gas-cooled reactor for ORNL(Column D), the General Atomics reactor for the Philadelphia Electric Company (Column E), and the Aero-Jet General Reactor for the Army (Column W).

Several others are in the authorized research and development phase, such as the General Nuclear Engineering Company pressure tube reactor (Column K), the Sanderson and Porter Company pebble bed reactor (Column L), and the General Atomics Company marine direct-cycle reactor (Column F).

The Kaiser-AC reactor(68) for ORNL is similar to the later British reactors except for the use of enriched fuel, stainless steel cladding, and helium gas as a coolant. This effects a net reduction in size. The reactor is well designed and should operate satisfactorily.

The General Atomics helium-cooled reactor for Philadelphia Electric Company(42) is very similar to the British Advanced Reactor Concepts, except that the former employs an indirect steam cycle. The fact that the No. 2 core employs UC and ThC canned in graphite tubes for fuel is an interesting development, as is the design feature of a fission product trapping system. The No. 1 core, however, uses stainless steel cladding. Since the exit gas temperature is 1382°F, this reactor could also be used in a direct closed cycle once helium turbines and compressors in this range are developed.

The Aero-Jet General Reactor (GCRE-I)(75) for the Army is a pressure tube design wherein the entire pressure tube assemblies, plenums, and associated mechanisms are totally immersed in a tank of H_2O. This is a small, unique military reactor designed to use H_2O, which is available in most areas, for moderator and reflector, and N_2 as a coolant, so that conventional air compressors and turbines may be used.

The General Nuclear Engineering Company D_2O-moderated and CO_2-cooled pressure tube prototype reactor(150) is aimed at the ultimate use of natural uranium as fuel.

The Sanderson and Porter Corporation pebble bed reactor(108,109) using graphite balls containing fissile or fertile material for fuel offers a flexible arrangement for the use of a combination of thorium and uranium. This design has an excellent potential since the problem of loading and unloading fuel is simplified. The Brown-Boveri-Krupp Combine in Germany are building a reactor similar to this, except that they are using a gas mixture of about 25% helium and 75% neon.

The General Atomics Marine Gas-cooled Reactor(45) is the only direct closed cycle concept being seriously considered. The successful development of this reactor would be a major advancement in reactor technology. The facts that gas outlet temperatures of 1300°F are contemplated and that beryllium oxide is used as a moderator are significant. Since the bulk gas is helium, one assumes that development work in helium turbines and compressors is in progress.

In general, the majority of the gas reactor proposals made to date are based on graphite as a moderator and reflector, and uranium dioxide fuel in a stainless steel matrix clad with stainless steel. The favored gas coolant is helium, followed by carbon dioxide and nitrogen. Few of the proposals specify the use of beryllium or beryllium oxide.

Some promising research has been done at Babcock and Wilcox[18] on the gas suspension principle, i.e., graphite dust suspended in gas. A marked increase in specific heat is claimed for this concept. The work done on the dust fuel[2] and flowable solids[38] concept is interesting; however, much development work must be done before they can be employed in a practical design.

In the high-temperature field, the Los Alamos Turret proposals[89,90] are interesting studies, as is the NDA[103] high-temperature process reactor. These concepts will require considerable research and development in high-temperature materials. There is much interest in the steam-cooled reactor concept by Babcock and Wilcox Company,[105] ORNL,[118] and Vickers Nuclear Engineering Ltd.[142] The attractiveness of this concept is based on the possible utilization of current material and turbine technology. At the present time, the Bureau of Mines, in cooperation with the AEC, is operating a facility using helium gas at 2200°F. This experiment, if successful, will ultimately result in a process for the gasification of coal, thus offering another use for a high-temperature gas reactor.

Sanderson and Porter, Inc., have in operation a facility at Fort Belvoir, Virginia, for experimentally testing high-temperature gas turbines. This parallels the work being done by Aero-Jet General[75] on the nitrogen-cooled reactor for the Army.

The American Society of Mechanical Engineers[152] has issued a comprehensive report on the progress being made in gas-turbine technology. The gas-turbine progress meeting proceedings of April 6, 1959, have been issued by the Office of the Director of Defense Research and Engineering.[165]

Some significant work by the ANL Metallurgy Division[10] on high-temperature fuel materials indicates that high heat fluxes are possible for long irradiation periods. Also, the Symposium on High Temperature Technology[161] indicates that considerable progress is being made in this field.

A very interesting recent development, mentioned in the November, 1959, issue of The Forum Memo, is the use of fuel elements at Idaho by the General Electric Company, made of one-eighth-inch diameter stainless steel wire containing fully enriched uranium dioxide. A similar wire fuel concept is the subject of report ANL-5590.[9]

A Summary of Fuel Types for Gas-cooled Reactors

One type (ORNL-Allis Chalmers)[111] uses rods of small diameter, containing the fissile material in oxide form in a compatible matrix, which is then enclosed in some type of metallic cladding. These unit parts are then assembled into a subassembly and inserted into a moderator.

A second type (General Atomic's Philadelphia No. 2 core)[42] contains the fissile material in either oxide or carbide form in a graphite matrix which is then encased in a graphite can. Thus, each fuel element is self-contained in its unit moderator.

A third type is the pebble-bed type (proposed by Sanderson and Porter)[108,109] which contains the fissile material in a graphite ball. These balls are then loaded in openings in the graphite moderator, much in the manner that a stove is loaded with coal.

A fourth type is described as the flowable solids reactor (developed by Fluor Corporation)[38] which employs crushed fused UO_2 in the form of a dry, granular, flowable powder, of about 200 microns (0.007874 in.), which circulates in graphite-moderator channels. A similar type is the dust-fueled type developed by Armour Research Foundation[2] wherein the fissile material (fully enriched UC_2) in the form of powder of about 10-micron (0.0003987-in.) particle size is mixed with gas and circulates through a graphite reflector.

A fifth type is some form of the Farrington Daniels concept,[147] i.e., a disposable, unclad graphite moderator containing coolant passages. The graphite is impregnated with uranyl nitrate and heated electrically, thus dispersing UO_2 throughout the graphite. The impregnated graphite is then soaked in pitch and reheated.

A sixth type involves a tubular fuel tube (proposed by Martin Company)[94] in which the fissile material, in oxide form, is encased in the tube wall. The unit tubes then are assembled into a unit subassembly for insertion into a moderator. This type offers a large ratio of heat transfer to volume.

A seventh type is the twisted ribbon concept of Du Pont,[34] in which a natural uranium matrix clad with either zirconium or magnesium is employed.

An eighth type is one employing coaxial tubes with stainless steel matrix and cladding for the Aero-Jet General[75] design.

A ninth type is a future concept proposed by General Nuclear Engineering Corporation[150] for use in a pressure tube core using natural uranium clad with finned beryllium tubing.

A tenth type is a liquid fuel, i.e., uranium in bismuth, proposed by Brookhaven National Laboratory.[129]

III. Conclusions

A. General Discussion

When a direct-cycle power recovery system is used, there is strong incentive to utilize gas temperatures as high as possible. With the stainless steel clad, UO_2 matrix fuel elements, 1600°F is the maximum feasible cladding temperature. This temperature would permit a bulk reactor outlet temperature of 1400°F, although current gas turbine technology limits the turbine inlet temperatures to 1300°F for continuous operation. With the indirect power recovery cycle, there is little incentive to attain coolant temperatures above 1200°F. This latter limit is based on the temperature limits of large central station steam plants presently under construction.

An examination of Table 1 indicates that beryllium, beryllium oxide, or other cermets have not been given much consideration as either fuel cladding, as a moderator and as a reflector, other than the brief report in Ref.(119) p. 6, and Ref.(159). Likewise, the majority of reactors now being given serious consideration are designed to use conventional turbo machinery which has an upper temperature limit of about 1250°F for turbine inlet temperatures for direct gas cycle systems and about 1050°F for indirect steam cycle systems. Some of the studies in the high-temperature range specify graphite as a moderator and as a fuel cladding. The graphite is unclad for use with helium and clad for use with carbon dioxide. The studies made in the high-temperature field, namely the Turret experiments at Los Alamo,[89,90] the Nuclear Development Associates proposals[102,103] and Oak Ridge National Laboratory reports[113,114,119] are interesting and outline many of the problems involved.

Conventional steam turbine practice limits the steam temperature to about 1050°F and 1450 psi for maximum efficiency. To achieve these turbine temperatures out of the heat exchanger in an indirect cycle gas reactor, an outlet gas temperature of about 1500°F is required.[114] If turbo machinery were available to operate with 1500°F gas inlet temperatures, then this gas temperature could be employed in a direct cycle with definite improvement in efficiency, which would result in lower power costs. To achieve this goal, a development program would be required for turbines, compressors, seals, expansion joints, and bearings.

A phase of the high-temperature field with a definite potential is that of process heat. In the Nuclear Development Associates Report,[103] a table, repeated in Fig. 10, lists many potential uses for high-temperature process heat. The National Planning Association[162] has issued an excellent report on nuclear process heat in industry. The Bureau of Mines[160] at Morgantown, West Virginia, has a research and development program for the gasification of coal using helium gas at temperatures above 2200°F. This work is done as part of a cooperative agreement between the Bureau and the AEC. The American Hydrotherm Corporation[108] also reports the potential applications of nuclear energy for process and space heat in the USA.

B. Status of Designs Now in Progress and Their Limitations

1. The Kaiser-Allis Chalmers experimental gas-cooled reactor for ORNL[68] is under construction. As stated before, this is a conservative design using a gas to water heat exchanger to produce 900°F steam. The inclusion of several experimental test facilities is an excellent feature. Since the gas coolant is helium, which is compatible with the graphite moderator, the design reactor outlet gas temperature of 1050°F can be increased with the advances in fuels technology. This reactor should provide a wealth of operating data.

2. The Aero-Jet General Army Program[71] is under construction. The H_2O-moderated design Phase 1, i.e., GCRE-1, is well along. This reactor employs an interesting coaxial fuel design. This design is limited only by the fuel cladding and by the ability of the gas circulating system to remove the heat generated in the fuel. A parallel program at Fort Belvoir, Virginia, by Sanderson and Porter, Inc.[106] is the closed-cycle gas turbine test facility. The results of these tests will be of vital interest to anyone engaged in the gas reactor program.

3. The General Atomics-Philadelphia Electric Company[42] high-temperature gas-cooled, graphite-moderated reactor is under construction. The operation of this reactor will be closely watched because of the use of fuel dispersed in graphite and the use of fission product trapping methods while the reactor is operating. The successful use of uranium carbide and thorium carbide as fissile materials in a graphite matrix will certainly be a matter of universal interest. This design has the potential for a high burnup rate; the only limitations are those of the steam system.

4. The design of the General Nuclear Engineering Company pressure tube reactor[150] is under evaluation. The problem, as with all pressure tube reactors, is the cost and integrity of the pressure tube system.

5. The design of the Sanderson and Porter, Inc. pebble bed reactor[108,109] is under evaluation. One problem is that of retaining fission products and another is the effect of long-time irradiation effects on

the shape and mobility of the graphite ball-type fuel. The design is certainly unusual and if the above problems can be resolved, this reactor may be the answer to low cost nuclear power. The fuel costs appear to be attractive.

6. The design of the General Atomics Marine Direct Cycle Reactor[45] is also under evaluation. The problem, once a high-temperature reactor fuel is developed, is to develop turbo machinery, compressors, seals and associated equipment to operate in this high-temperature environment. The direct-cycle principle offers much in possible economics in power costs and in reduction of plant size.

C. Status of Current Materials and Their Limitations

1. Moderators

The subject of moderator selection for a high-temperature gas-cooled reactor is a very complex one and difficult to condense for a summary report. However, some excellent reporting has been done by General Atomics[39-47], by General Electric Company[64-66], and by Oak Ridge National Laboratory[111-118] on this subject. The materials generally considered are graphite, zirconium hydride, water, and beryllium oxide. At the present time, most active projects use graphite as a moderator. Some studies have been made on the use of zirconium hydride,[41] heavy water,[34,133,150] light water,[75,118,148] and beryllium oxide.[45,159]

Each moderator selection is highly dependent on its compatibility with the coolant used. Hence, the combination of graphite and helium is the one most in favor.

2. Fuels

Most of the reactor proposals specify UO_2 fuel clad with stainless steel, which is at this time the most practical fuel concept. If the problem of the escape of fission gases can be resolved as expected in the General Atomics[42] No. 2 core, then the graphite-clad fuel can be used to advantage. The new developments in ultrapure beryllium and niobium metals offer promise that these may be used as potential cladding materials. Most of the national laboratories are maintaining development programs of varying magnitude on cermet fuel types. Any real advancement in high-temperature technology will depend on the success of these programs.

3. Structural Materials

The combined operating conditions of high temperatures, pressures and radiation fluxes impose serious limitations on structural materials for reactor use, therefore a development program of considerable scope is required to create new materials to fill this need.

4. Equipment

In an indirect-cycle reactor, i.e., transfer of heat from gas to water for steam generation, the problem of high-temperature heat exchangers must be resolved. Possibly molybdenum, tantalum, or niobium alloys may be useful. In a direct cycle, gas turbines and compressors should be designed for the particular gas to be used in order to attain the highest efficiency. Also, gas seals, bearings and expansion joints must be developed for use in this rigorous environment.

D. Research and Development Programs Underway

One of the principal problems is that of compatibility of combinations of gases and materials at high temperatures; therefore, current high-temperature gas-cooled reactor programs are backed up with considerable research effort in this direction. The General Atomics Report[41] and the General Electric Reports[64,65] deal very thoroughly with this subject.

In connection with research on high-temperature materials, much of this effort currently is directed to the missile program. Also, much of the ANP metallurgical research at Battelle and elsewhere is highly pertinent to any high-temperature reactor development.

In the equipment field, supporting research is in progress on all elements entering a high-temperature gas reactor system. Also, research in the airplane industry on turbo machinery[165] can be applied to nuclear power systems.

IV. Recommendations

A. Reactor Design Recommendations

In view of the practically untouched potential in high-temperature gas applications, a gas reactor program is proposed as follows.

A versatile prototype of a reactor system to be called the Gas Reactor Complex, consisting of a reactor for high-temperature experimentation, employing removable moderator and reflector cells, and a series of fuel components, a process heat experimental zone, and a zone for power take off. Typical reactor systems are shown in Figs. 2A, 2B and 2C. A typical reactor cross section is shown in Fig. 3 and suggested fuel types in Fig. 4. No attempt has been made to calculate heat generation, criticality and gas flow, other than to assume a heat flux of about 100,000 Btu/(hr)(ft^2) for comparison purposes. A suggested starting goal would be a gas outlet temperature of 1800°F minimum, using a beryllium oxide moderator cell and a UO_2 fuel rod clad with niobium, beryllium oxide, or aluminum oxide per Fig. 4.

The gas coolant would be carbon dioxide. An alternative beginning would be to use a moderator cell of high-density graphite (density 1.9 gm/cm^3) and helium gas as a coolant.

Figures 2A, 2B, and 2C are circuit diagrams of three possible reactor systems. The system in Fig. 2A is comprised of a reactor in which the cool gas enters near the top, circulates downward through the thermal shields, and then upward through the core. The proposed pressure vessel material would be inconel "X" or some heat-resistant alloy. The hot gas circulates through a gas-to-air heat exchanger, a blower, and back to the reactor inlet side. The heated air from the heat exchanger passes through two circuits, on to a process station where heat is rejected, and to a second where the air enters an air turbine which is coupled to a generator. The air is then recirculated back to the heat exchanger. Thus process heat may be obtained and power generated from the same coolant line. In Fig. 2B, the system is the same for the primary gas system; however, the secondary system employs a steam generator to use conventional steam turbo machinery. In Fig. 2C the cool gas enters at the top, circulates down through the thermal shields, and then upward through the core. The hot gas circulates through the process station, then on to a direct-cycle turbine system, and back to the reactor. A variation of this concept would be to omit the process station and only generate power.

Other combinations are possible; for example, it may be possible to use an open-cycle air turbine on the secondary side of the heat exchanger. Also, it may be possible to utilize the exit air from the process zone to operate a reciprocating piston engine.[30] Another arrangement would be to discard the entire secondary system and use a heat sink in the event the reactor is to be used for fuel experimentation only. An installation of this type would be extremely versatile and would permit a thorough investigation of all phases of the high-temperature gas-cooled reactor concept, including fuel, moderator, and reflector evaluation, a program of process heat experimentation, and finally the testing at high temperatures of advanced turbo machinery. All of this may be done in one installation.

One of the serious problems involved in the high-temperature process system is the design of a high-temperature gas-to-air heat exchanger. The heat exchanger, in the author's opinion, is preferred over circulating the reactor bulk gas through the process station and turbo machinery. Use of the heat exchanger eliminates the problem of activation of the process and turbine stations. Since, at the present time, no turbine machinery exists to operate at ultra high temperature, no great penalty is paid by introducing a secondary circuit. Bearing in mind that the 1800°F bulk gas outlet temperature is only a suggested beginning point, increased temperatures are possible when advances are made in materials technology.

B. Materials

1. Moderators

As mentioned earlier, graphite is the favored moderator, although beryllium oxide is now receiving considerable attention. A material seldom discussed is high-density graphite. The density of conventional reactor-grade graphite is about 1.70 gm/cm^3, yet the Carbon Companies have produced graphite with a density of 1.90 gm/cm^3. Although this material is relatively costly, due to lack of demand, its use may effect a reduction in the reactor size. Strangely enough, there are no data available on the nuclear properties of this material, and it is suggested that these be investigated.

2. Fuels

In the moderator cell mentioned previously, various fuel concepts could be tested as follows:

Figure 5A - Niobium or beryllium-clad tubes similar to the Martin Company's fuel concept. With some development work, tubular shapes of aluminum oxide, beryllium oxide, or possibly of some carbide could be used. The matrix would be enriched UO_2 or UC.

Figure 5B - A wire mesh element with an enriched UO_2 oxide core clad with stainless steel, niobium or beryllium.

Figure 5C - A plate element, clad with beryllium oxide or aluminum oxide, with enriched UO_2 or UC matrix.

Figure 5D - A flat plate made of graphite, oxide, or carbide containing fissile material. This placque contains coolant holes and is stacked in a moderator cell.

Figure 5E - Some form of pebble bed similar to the Sanderson and Porter Concept[110] using dense graphite or beryllium oxide cladding and a UO_2 or UC matrix. The balls would be randomly packed in an oxide can for easy removal.

Figure 5F - This is an unrestricted channel concept in that a cermet moderator cell might be used to contain a fluidized bed or possibly some homogeneous type of fuel.

3. Structural Materials

The need is for a well-organized program to determine the long-term irradiation effects on known structural materials, particularly the effect on creep and stress-rupture characteristics. From the results obtained, perhaps some direction for future experimentation can be resolved.

The ANL Metallurgy Division is now doing some development work with cermets involving such materials as UC, PuC, Silica-ZrO_2, Al_2O_3, and BeO. Likewise, some development work is being done on niobium, vanadium, and molybdenum metals and alloys, and on uranium and thorium sulphides. All of these programs are aimed at high-temperature operations.

C. Gas Coolants

It must be emphasized that in cases where bare graphite is used, it is necessary to use helium or nitrogen gas as a coolant, due to the reaction between graphite and CO_2 at elevated temperatures. The author prefers the use of CO_2 over helium as a coolant because of the difficulties of containing helium and the cost involved in the loss of this gas. Calder Hall(5) reports considerable difficulty in containing CO_2 at 100 psi with a consistent loss of about one-half ton per day. Helium gas has about one-tenth the density of carbon dioxide at S.T.P., has about five times the specific heat at S.T.P., and costs about five times more. Balancing these factors, the author opines that the preferred coolant is carbon dioxide. If, however, the problem of containment can be resolved, then the preferred gas would be helium. The compatibility of carbon dioxide and helium with various oxide fuel claddings should be explored.

A third coolant possibility is nitrogen. Battelle has evidence that additives that prevent nitriding may be used. The current reactor for the Army(75) should resolve many of the questions regarding the use of nitrogen. The author, however, sees no outstanding long-term advantage of the use of nitrogen. Its basic attractiveness is due to the fact that the density, being practically the same as air, permits the efficient use of conventional air compressors and air turbines. As a matter of general interest, the author has again explored the possibilities of neon gas as a coolant, primarily because of its proposed use in the Brown-Boveri Reactor Project in Germany. Research is continuing at Linde Division of Union Carbide Corporation(164) on the use of neon gas; however, the cost remains too prohibitive for reactor use.

D. General

The development work required may be divided into four basic categories. The first is metallurgical, in that high-temperature fuel alloys must be developed, moderator materials investigated, the compatibility of fuel and moderator materials with various gases investigated, and, lastly, a review of structural materials as regards to their high-temperature physical properties.

The second category would be a program to investigate high-temperature, high-velocity gas heat transfer.

The third category would be the broad field of high-temperature instrumentation.

The fourth category would be component testing, including turbines, compressors, bearings, expansion joints, and seals. The work required in the third and fourth categories had best be developed by outside firms who specialize in these items but tested in this reactor.

The proposed versatile prototype is intended to provide a universal high-temperature test facility not available in reactors now under construction, i.e., above the 1800°F temperature range. The only similar installation is the Los Alamos Turret Experiment[90] which uses a graphite moderator.

In connection with some of the reports studied,the author believes that three concepts are exceptional in their potential: The Sanderson and Porter pebble-bed reactor,[108, 109] because of the simplicity of refueling, the Babcock and Wilcox gas suspension concept,[16,17,18] because of the greater heat capacity of the gas, and the General Atomic direct closed cycle system,[39,40,41,45] because of the potential for high efficiency.

In closing, the author believes that a versatile high-temperature gas reactor experimental facility as described can contribute greatly to the ultimate goal of competitive power generation and to increase the potential of reactors for process use.

V. Details of Survey

A. Gas Reactor Synopsis

A Brief Description of Representative Gas-cooled Reactor Types

GCR2 (ORNL-2500)[111] - This is helium-cooled and graphite-moderated, using 2% enriched UO_2 pellets, clad with stainless steel, as fuel. The helium circulates through a heat exchanger where steam is generated, similar to the British Calder Hall designs. The efficiency is 32.8%.

Kaiser-AC (IDO-24027)[68] - Preliminary designs used CO_2 as a coolant. However, this was changed to helium in the final design. This prototype reactor is helium-cooled, and graphite-moderated, using 2.2% enriched UO_2 pellets, clad with stainless steel, as a fuel. The helium circulates through a heat exchanger where steam is generated. The reactor is rated at 84.3 Mwt, the average heat flux is 66,833 Btu/(hr)(ft^2), the exit gas temperature is 1050°F, and the pressure is 315 psia. This design is similar to the British Calder Hall and ORNL designs. The efficiency is 30.5%.

Philadelphia Electric Gas-cooled Reactor (General Atomic GA-593)[42]

Design No. 1, Metal-clad Core (30 Mwe) - This is helium-cooled and graphite-moderated using U^{235} and Th^{232} in carbide form in a graphite matrix. The ratio of U^{235} to Th^{232} is 0.21253. The fuel cladding is graphite plus a membrane of either stainless steel or niobium. This is an indirect-cycle process, the helium passing through a heat exchanger where steam is generated. The reactor is rated at 88.6 Mwt, the average heat flux is 67330 Btu/(hr)(ft^2), the exit gas temperature is 1015°F, and the pressure is 294 psia. Efficiency is 32.2%.

Design No. 2, Graphite-clad Core (40Mwe) - This, also, is helium-cooled and graphite-moderated, using U^{235} and Th^{232} in carbide form in a graphite matrix. The ratio of U^{235} to Th^{232} is 0.15966. The cladding is graphite. This, also, is an indirect-cycle process, the helium passing through a heat exchanger where steam is generated. The reactor is rated at 115 Mwt, the average heat flux is 87441 Btu/(hr)(ft^2), the exit gas temperature is 1382°F, and the pressure is 294 psia. The efficiency is 34.8%.

He Gas-cooled Maritime Reactor (General Atomics)[45] - This is helium-cooled and beryllium oxide-moderated, using 20.0% enriched UO_2 pellets, clad with stainless steel, as fuel. It is a direct closed-cycle design. The reactor is rated at 53.3 Mwt. The average heat flux is 55340 Btu/(hr)(ft^2), the exit gas temperature is 1300°F, and the pressure is 760 psig. Net efficiency is 32.9%.

CO_2 Gas-cooled Maritime Reactor (General Atomic GA-570)[39,40,41] - This is CO_2-cooled and graphite-moderated, using 27.1% enriched UO_2 pellets, clad with stainless steel, as fuel. It is a direct closed-cycle design. The reactor is rated at 45.9 Mwt. The average heat flux is 56200 Btu/(hr)(ft^2), the exit gas temperature is 1300°F, and the pressure is 851 psig. Net efficiency is 32.5%.

CO_2 Gas-cooled ZrH_2-Moderated Maritime Reactor (General Atomics GA-570)[39,40,41] - This is CO_2-cooled and ZrH_2-moderated, using 5.75% enriched UO_2 pellets, clad with stainless steel, as fuel. It is a direct closed-cycle design. The reactor is rated at 45.0 Mwt. The average heat flux is 106700 Btu/(hr)(ft^2), the exit gas temperature is 1300°F, and the pressure is 1765 psig. Net efficiency is 31.4%.

In addition to the four preceding designs, General Atomic also presents in GA-570 a preliminary evaluation of the following concepts:

1. Heavy water-moderated, CO_2-cooled reactor
2. Heterogeneous BeO-moderated, CO_2-cooled reactor
3. Homogeneous graphite-moderated, helium-cooled reactor
4. Homogeneous BeO-moderated, helium-cooled reactor
5. Heterogeneous graphite-moderated, helium-cooled, indirect steam cycle reactor.

Florida Gas-cooled Pressure Tube Reactor (GNEC)[150] - This is a CO_2-cooled, D_2O-moderated pressure tube reactor, using 1.84% enriched UO_2, clad with stainless steel, as fuel. The carbon dioxide circulates through the pressure tubes and into a heat exchanger where steam is generated. The reactor is rated at 173 Mwt. The average heat flux is 95300 Btu/(hr)(ft^2), exit gas temperature is 1050°F and pressure is about 500 psig. Efficiency is about 30.6%.

Pebble-bed Reactor (Sanderson and Porter Company, Alco Products - NYO-2373, NYO-8753)[108,109] - This is helium-cooled and graphite-moderated, using $1\frac{1}{2}$ -in.-diameter graphite balls impregnated with fissile material as fuel. The core is made of graphite, thorium oxide, and uranium oxide in the atom ratio of 3745-11-1; the blanket is made of graphite and thorium oxide in the atom ratio of 22-1. The reactor is designed for the thorium U^{233} cycle, but, also, may be used as a U^{235}thorium breeder and as a U^{235} plutonium converter. The helium gas is circulated through the core and blanket to a heat exchanger where steam is generated. The reactor is rated at 337 Mwt. The gas outlet temperature is 1250°F and the pressure is 965 psia. The efficiency is 37%.

15-Mw Gas-cooled Closed Cycle Reactor (Ford Instrument Company FICO-101)[35] - This is nitrogen-cooled and graphite-moderated, using 10% enriched UO_2 formed into hexagonal shapes which include cooling passages. These passages and the exterior are clad with stainless steel. It is a direct closed-cycle design. The reactor is rated at 44 Mwt. The gas outlet temperature is 1300°F and the pressure is 765 psia. The efficiency is 34%.

Turret Experiment (Los Alamos-Sandia LA-2303)[90] - This is helium-cooled, and graphite-moderated, using graphite fuel tubes impregnated with fully enriched U^{235}. Since this is a high-temperature experiment, no power is generated. The reactor is rated at 3 Mwt, the exit gas temperature is 2400°F, and the pressure is 500 psi.

In addition to the foregoing proposal, Los Alamos in report LA-2198,[89] also proposes a high-temperature-gas, closed-cycle reactor.

The reactor is conceptual and uses N_2 as a coolant. The cycle is a closed direct one with exit gas from the reactor at 1300°F and 520 psia. The fuel is unclad graphite tubes impregnated with fully enriched uranium. The efficiency is 30.3%.

Gas-cooled, Natural Uranium, D_2O-moderated Power Reactor (ORSORT, CF-56-8-207)[24] - This is a study report only. The reactor is helium cooled, D_2O moderated, and graphite reflected, using natural uranium fuel clad with zirconium. The exit gas is circulated to a heat exchanger where steam is generated. The exit gas temperature is 1000°F and the pressure is 464 psia. The efficiency is 21.4%.

Flowable Solids Reactor (Fluor Corporation FLR-1)[38] - This is a preliminary evaluation study of a flowable solids reactor in which the reactor fuel, presumably crushed fused UO_2, is in the form of a dry, granular flowable powder with a particle diameter of about 200 microns, i.e., 0.007874 in. This material flows by gravity down through vertical fuel channels spaced in a graphite moderator. At the bottom of the channel, an orifice restricts the flow rate of the fuel and maintains a constant fuel density in the core. A helium atmosphere of 14.7 psia is maintained in the system. The fuel, heated to about 2000°F, cascades over steam generator tubes. The steam probably would be radioactive. The reactor is rated at 320 Mwt with a fuel enrichment of 0.98%. The efficiency is 31%.

Armour Dust-fueled Reactor (Armour Research Foundation, AECU-3909)[2] - This is a reactor using UC_2 powder of about 10-micron (0.003987-in.) particle size. The UC_2 is fully enriched and suspended in He. The combined fuel and coolant circulate through a heat exchanger where steam is generated. The reactor outlet temperature is 2500°F; the heat power rating is 500 Mwt. No efficiencies are given.

Babcock & Wilcox Gas Suspension Experiment (BAW-1159)[18] - This experiment increases the heat capacity of gas by suspending fine graphite particles in the gas coolant. The experiment was done with He and N_2 gas.

He-cooled, D_2O-moderated Pressure Tube Reactor (Du Pont, DP-307)[34] - This is one of a series of three evaluation studies of gas-cooled, D_2O-moderated reactors using natural uranium fuel in the form of zirconium-clad twisted ribbons. The helium circulates through a heat exchanger where steam is generated. The reactor is rated at 313 Mwt, the average heat flux is 63846 Btu/(hr)(ft^2), the exit gas temperature is 1052°F, and the pressure is 400 psig. Efficiency is 32%.

<u>N_2-cooled, D_2O-moderated Pressure Tube Reactor (Du Pont, DP-307)</u>[34] - This reactor is nitrogen cooled and heavy water moderated, using natural uranium fuel in the form of magnesium-clad twisted ribbons. The nitrogen circulates through a heat exchanger where steam is generated. The reactor is rated at 377.4 Mwt, the average heat flux is 77940 Btu/(hr)(ft^2), the exit gas temperature is 714.2°F, and the pressure is 400 psig. Efficiency is 26.5%.

<u>CO_2-cooled, D_2O-moderated Pressure Tube Reactor (Du Pont, DP-307)</u>[34] - This reactor is carbon dioxide cooled and heavy water moderated, using natural uranium fuel in the form of magnesium clad twisted ribbons. The carbon dioxide gas circulates through a heat exchanger where steam is generated. The reactor is rated at 356 Mwt. The average heat flux is 61200 Btu/(hr)(ft^2), the exit gas temperature is 689°F, and the pressure is 600 psig. Efficiency is 22.75%.

<u>Nuclear Gas Engine (ORNL CF-58-9-12)</u>[30] - This is a reactor system using a reciprocating engine to create power. The working fluid is nitrogen and the moderator is graphite. The fuel is slightly enriched UO_2, clad with stainless steel. The heated gas is expanded in a clyinder to move a piston. The efficiency is 30%.

<u>Army Gas-cooled Reactor Program (Aero-Jet General IDO-28507)</u>[75] - There are four programs in force. The first phase called GCRE-1 is a small heterogeneous, H_2O-moderated, N_2-cooled, direct-cycle reactor using stainless steel-clad coaxial fuel tubes. The second program is called GCRE-2, and is a homogeneous, graphite-moderated reactor. The third phase is called ML-1 (Mobile Low Power) reactor. The fourth phase is called the Gas Turbine Test Facility.

In addition to the foregoing, Sanderson and Porter, Inc. (NP-6487)[106] are running an N_2 closed-cycle gas turbine test facility for the Army at Ft. Belvoir.

<u>Gas-cooled Reactor Power Plant (Walter Kidde Nuclear Laboratories, WKNL-46)</u>[139] - This is a military plant combining electrical power generation and heat generation. It is a closed-cycle, helium-cooled, graphite-moderated reactor. The thermal output is 1112 kwt. The electrical output is 100 kw and the usable heat output is 400 kw. The reactor exit gas temperature is 1150°F and the pressure is 164 psig.

<u>Closed-cycle Gas Turbine Power Plant (American Turbine Company, ATC 54-12)</u>[15] - This is a direct closed-cycle reactor proposal. The report does not cover the reactor, only the power-generating phase. The coolant is helium. The reactor exit temperature is 1400°F at 985 psia. The efficiency is 40%.

Helium-cooled, Direct Closed-cycle Reactor (ANL, TID-2508, Vol. 1A)(130) - This is a closed, direct-cycle, helium-cooled, graphite-moderated reactor. The helium gas exits from the reactor at 1400°F and 997 psig, and expands directly into a turbine. The fuel is stainless steel-clad thorium enriched with U^{233}, the reactor is rated at 189 Mwt, and the efficiency is 32.5%. This reactor is designed to function with a power generation scheme similar to the above American Turbine Company system.

Gas-cooled Graphite UO_2 Power Reactor (F. Daniels)(147) - This is a proposal to impregnate unclad graphite with UO_2 and to circulate helium gas in a closed circuit into a gas-to-air heat exchanger. The heated air is circulated in a closed cycle to a turbine. Not much data is given in the memorandum.

Gas-cooled Marine Reactor (General Motor Company TID-5510)(131) - This is a direct closed-cycle, helium-cooled, graphite-moderated reactor. The reactor exit gas temperature is 1300°F and the pressure is 1000 psig. The reactor is rated at 55 Mwt at an efficiency of 29.8%.

Marine Gas-cooled Reactor (American Standard, ASAE-S5)(14) - This is a marine helium-cooled reactor using a direct closed cycle. Part of the exit gas is passed through a steam generator for the auxiliary load. The reactor is graphite moderated and reflected, and uses 4.0% enriched UO_2 clad in stainless steel for fuel elements, which are in the form of concentric rings. The reactor is rated at 53 Mwt and the SHP efficiency is 28.3%. When the auxiliary and hotel loads are included, the efficiency is much higher.

A Study of a Gas-cooled Reactor; Closed-cycle Gas Turbine Power Plant for Large Central Station Use (Proposal to AEC dated August 27, 1957, by Jackson & Moreland, Inc.)(148) - This is a CO_2-cooled, H_2O-moderated and reflected reactor, using slightly enriched UO_2 clad with stainless steel as fuel, with aluminum pressure tubes. The hot exit gas is circulated directly to the turbine. The reactor exit gas temperature is 1400°F, and the pressure is 1080 psi. The reactor is rated at 1000 Mwt and the net efficiency is 30%.

Experimental Reactor for High Operating Temperatures (Nuclear Development Company NDA 64-101)(103) - This is an unusual design in that it is a two-zone reactor, called HOTR, for process heat. Helium is used as a coolant in the hot inner zone. Some form of ceramic fuel elements encased in impervious graphite is used in this region. Fuel is to be in the form of rods, tubes or spheres. The moderator is graphite. The exit gas temperature is 2500°F. The outer zone uses H_2O coolant and MTR type fuel elements.

Brookhaven National Laboratory, (TID-2506)(129) - This is a liquid metal fueled (uranium in bismuth), helium-cooled, graphite-moderated, direct cycle power reactor. The core contains horizontal and vertical passages for the coolant and the liquid fuel. The gas outlet temperature is 1400°F at 1000 psig. The reactor is rated at 148 Mwt and the efficiency is 40.4%.

Hanford Atomic Products, Operation, (General Electric Company, HW-54727)(64) - This is a direct-cycle, helium-cooled, graphite-moderated reactor, using slightly enriched UO_2 fuel clad with stainless steel. The gas outlet temperature is 1300°F and the reactor is rated at 1000 Mwt.

A Steam-cooled, Heavy Water Reactor (Vickers Nuclear Engineering Y113)(142) - This is a steam-cooled, D_2O-moderated, H_2O-reflected, indirect cycle reactor using a pressure tube type of construction. The fuel is slightly enriched UO_2, clad in stainless steel. The reactor is rated at 150 Mwt, and the efficiency is not stated.

The HGCR-1 Reactor (Oak Ridge National Laboratory, ORNL-2653)(114) - This is a hot gas-cooled reactor and no fuel cladding is used. It is a helium-cooled, graphite-moderated, indirect cycle design, using slightly enriched UO_2 in a graphite matrix as fuel. The reactor is rated at 3095 Mwt and 300 psig. The efficiency is 36.5%.

A Preliminary Study of a Direct-cycle Steam-cooled Reactor for Merchant Ship Propulsion (ORNL-2759)(118) - This is a direct-cycle, steam-cooled reactor with H_2O moderator and a beryllium oxide (canned in aluminum) reflector. The steam circulates directly to the turbines. The reactor is rated at 73 Mwt. The average heat flux is 158000 Btu/(hr)(ft^2). The exit steam temperature is 860°F and the pressure is 860 psig. The net efficiency including auxiliary load is 21%.

"Dragon" project (NP-9161)(153) - This is a cooperative European experiment designed to investigate the problems involved in the operation of a high temperature gas cooled reactor. The reactor is graphite moderated and helium cooled. The fuel is contained in a sheath of graphite with a matrix of graphite, uranium and thorium. Fission gases are bled out of the fuel rod during operation. The reactor is rated at 20 Mwt, the average heat flux is 76093 Btu/(hr)(ft^2), the exit gas temperature is 1382°F and the pressure is 294 psig. No electric power is produced.

B. Remarks from References

HW-54727[64] Add., Section VII, Page 1 - The perfect gas laws can be used to calculate cycle efficiencies when helium is the coolant; for other gases, the use of a Mollier diagram is mandatory.

As would be expected, the cycle thermal efficiency is raised by (1) increasing the cycle maximum temperature; (2) decreasing the cycle minimum temperature; (3) increasing the generator effectiveness; and (4) decreasing the system pressure losses.

In most cases, the reactor ΔT can be increased through wide limits with negligible effects on thermal efficiency. This increase in reactor ΔT reduces the required mass flow per kw electric, but increases the cycle pressure ratio.

Based on minimum cost per kw electrical, a plant utilizing carbon dioxide is the best, next would be the use of helium and nitrogen.

Helium, although requiring larger volume flows, requires the smallest flow area because it has a high sonic velocity. Also the piping pressure losses for helium will be lower than for other gases, even when helium is run through smaller ducts.

For the reactor and power plant designs considered by G.E., the cycle efficiency is reduced as specific power and reactor power are increased. However, the point of maximum cycle efficiency does not necessarily give the design for the lowest power (mills/kw).

HW-54727[64] Add., Section V, Page 7 - Carbon dioxide reacts with graphite at temperatures of about 600°C (1112°F). Therefore, the use of carbon dioxide in conjunction with graphite is limited to maximum graphite temperatures of 1112°F. Hydrogen is highly inflammable. Carbon dioxide carburizes ferrous materials at high temperatures. Nitrogen also reacts with ferrous metals at high temperatures, has a low specific heat, and, when irradiated, forms the long-lived isotope C^{14}. Argon has a low specific heat, and also forms the radioactive isotope A^{41}. Neon is prohibitively expensive, although the cost might be justified for military use.

HW-54727[64] Add., Section V. Page 3 - With graphite moderators and considering all factors, helium is the preferred coolant, although it requires higher volume rates, a greater number of stages on the compressor and turbine equipment, and is more difficult to contain. Yet, next to carbon dioxide it will give the highest plant efficiency, lower pumping power losses, and will require the smallest reactor rating for a given plant output. The second choice would be between carbon dioxide and nitrogen. Thermodynamically, carbon dioxide is preferred over nitrogen and will require a smaller turbine and reactor thermal rating. However, because the temperature limitation of carbon dioxide with graphite is about 1200°F, nitrogen would be the second choice. However, its use may require special treatment of piping materials because of the nitriding effect. (Author's note: The foregoing conclusions are valid only with a graphite moderator. If, for example, Be, BeO, or ZrH_2 were used as a moderator, probably carbon dioxide would be the preferred selection, considering, of course, the temperature limitations.)

HW-54727[64] Add., Section V, Page 8 - Presently available fuel elements, UO_2 with stainless steel cladding, limit maximum cycle temperatures to 1200-1300°F. If ceramic fuel elements are developed, the maximum cycle temperature could be increased to 1800°F or higher.

HW-54727[64] Add., Section VII, Page 5 - Present maximum cycle gas temperatures are limited by the allowable inlet temperatures of the turbine. For the present, with standard materials, this limit is 1300°F. This also represents a temperature limit imposed by existing fuel elements.

HW-54727[64] Add., Section II, Page 1 - Massive uranium is not acceptable as core material because of distortion that occurs with long exposures.

Helium or one of the other inert gases most desirable for unclad fuel.

Only limitation as to chemical activity in using unclad fuel is reaction of carbon dioxide with UO_2 at 932°F.

Limited data available indicate use of UC limited to below 2012°F because of reaction with nitrogen.

Limited data indicate that UC is stable at high temperatures.

Stainless steel, graphite, and zirconium seem to be the best cladding materials.

HW-54727[64] (Rev. Page 5) - Net power costs for operation with helium coolant are consistently and significantly lower (approximately 1-3 mills kwh) than for corresponding cases with nitrogen. This is caused by the increased reactor pressure drop due to the higher density of nitrogen.

The optimum goal exposure for the reference fuel used in the study appears to be approximately midway between 5000 and 10000 Mwd/T for a 6-inch lattice, whereas the optimum exposure for the 8-inch lattice would be closer to 10000 Mwd/T. The data presently available for pile physics calculations at the higher exposures are less reliable than those for 5000-Mwd/T exposure. Since the calculated difference in net power cost resulting from extending exposures from 5000 to 10000 Mwd/T, even in the maximum case, amounts to less than 0.5 mill/kwh, it seems more reasonable to accept an upper limit of 5000 Mwd/T for any reference fuel design, with the goal of extending exposures when more exact data become available.

The indirect-cycle cases, especially at higher power levels, are extremely sensitive to reactor ΔT, whereas the direct-cycle cases are relatively unaffected by nominal differences in ΔT, particularly at the lower specific tube powers.

Enrichment requirements for the lowest net power cost did not exceed 1.6% for the direct cycle and 1.3% for the indirect cycle. For the recommended direct cycle case of 1000 Mwt and 5000 Mwd/T burnup, enrichment should not exceed 1.25%.

Net fuel costs optimized fuel loadings in the range of 70 to 80:1 for the graphite to uranium ratio (atom to atom) at 5000 Mwd/T.

Within the range of coolant temperatures studied, i.e., 1000°F to 1400°F, the use of pressure-containing process tubes rather than the enclosing pressure vessel concept is not feasible due to the excessive fuel enrichments required to compensate for stainless steel process tubes. At lower coolant temperatures, the use of process tubes may prove feasible, but was not considered in detail.

<u>HW-54727[64] Rev., Page 29</u> - Croloy 15-15N is recommended for cladding because of excellent high-temperature characteristics.

<u>HW-54727[64] Rev., Page 36</u> - Helium, nitrogen, carbon monoxide, carbon dioxide, and argon were considered as potential coolants in the 1000°F-1400°F reactor bulk outlet range. The compatibility of the chemical and nuclear properties of the gases with cycle equipment fuel element limits, thermodynamic and heat transfer properties, equipment size, cost and expected design problems, was considered and compared for these gases. Briefly summarized, it was found that, for a graphite-moderated reactor, helium is the best coolant. Carbon dioxide will yield the highest plant efficiencies and require the lowest turbine and reactor rating for a given plant electrical capacity, but is not compatible with the open graphite fuel channel in the range of moderator temperatures considered.

<u>IGT-R-20[88] (Calder Hall Reactors)</u> - Carbon dioxide becomes radioactive during operation mainly because of A^{41}, formed by the irradiation of argon in the residual traces of air, and N^{16} produced by the neutron reaction in carbon dioxide. The dose rate at the surface of the unshielded heat exchangers is about 9 mr/hr, which is tolerable, and no shielding is required for maintenance work.

GA-87[39] Part 2 - Reports on development work on the fabrication of zirconium hydride.

UN Paper P/1077[57] - Suggests use of BeO, ZrC, SiC, and BeC as moderators. Also indicates need of cladding oxide fuels because of corrosion.

UN Paper P/312[53] - Paragraph 11 states that in the Calder Hall Reactor the leakage of one-half ton/day of carbon dioxide (corresponding to a hole 0.030 in. in diameter in a surface of 250,000 ft^2) was originally two tons/day, but was reduced by using vacuum industry techniques.

IDO-28538[84] Page 21 (Aero-Jet) - Considers using a mixture of graphite and BeC as a moderator, and also suggests that the use of zirconium-hydride in place of beryllium as a reflector does not change effectiveness very much.

NYO-8753[110] pp. 3-5 - The Minnesota Mining and Manufacturing Company is developing a coating for graphite which will give an impervious skin. This coating is known as 3M Ceramic "S" and has protected graphite against oxidation in air for 200 hours at 1400°C (2552°F).

Power Reactor Technology, June 1959, Page 62 - Battelle states that nitrogen can be used if nitriding preventatives are added.

UN Paper P/1157[60] - The French, in the G2 and G3 reactors, prefer the magnesium-zirconium alloy (0.6% Zr). Extrusions were made at 350°C (662°F) at a rate of four to six meters/minute. Also suggests 1.0% to 1.5% Mo as a magnesium alloying agent, and also beryllium.

ORNL-2767[119] Page 6 - Two new advanced reactor concepts are proposed. The first consists of a small diameter GCR-2 (Philadelphia Electric) type of core and a steam generator heat transfer matrix incorporated into a single pressure vessel. The second design consists of a small BeO-moderated core cooled with carbon dioxide at 1000 psi. Both of these designs indicate an excellent potential which should be resolved by continued development work.

Atomic Energy Applications with Reference to Underdeveloped Countries, Page 13 - States that full utilization of nuclear process heat is attained only when bulk exit temperatures are in the neighborhood of 2500°F. The most advanced work in this field is done by the AEC with the cooperation of the Bureau of Mines.[160] This agency is interested in the use of reactor heat to gasify coal.

GA-593[42] Page 1-3 - Why gas cooling? The aim is to achieve really economical nuclear power production by combining the high temperature potentialities of gas cooling with the high power density of pressurized water systems and to minimize the cost and difficulty of fuel reprocessing by a high degree of fuel utilization per charge. Among the types of reactors showing promise for this purpose, is one employing gas cooling of fuel elements which contain a solid homogeneous mixture of graphite moderator, a small proportion of U^{235}, and a relatively large amount of Th^{232} in the form of carbides.

The problem of applying gas cooling to reactors which use enriched uranium as a fuel is different from applying it to a natural uranium-fueled reactor. Essentially, the difficulty of using natural uranium in reactors is that without enrichment, fuel elements having a low surface to volume ratio, i.e., round rods, and pitched in a relatively widely spaced lattice, must be used to achieve sufficient reactivity in reasonable core sizes. As a consequence, the amount of fuel surface area that can be accommodated in a given core volume is greatly restricted, and extended surfaces (fins) must be used on the fuel element to obtain anything like acceptable heat transfer. As a result, a large quantity of neutron-absorbing material must be introduced into the core. If working temperatures are low enough to permit the use of aluminum or magnesium fins, very acceptable performance can be obtained, but only at the expense of having a very bulky plant. Economical use of such reactors is thus restricted to high-load factor operation, and then only under favorable financial arrangements. Furthermore, because there are no high-temperature canning materials which offer anything like the combination of good conductivity, cheapness, and the low absorption of aluminum or magnesium, the operation of this type of reactor at high temperature is distinctly limited. It appears, then, that finning can be used effectively only in low-power density systems operating at modest temperatures. However, with the use of enriched fuel, the situation is different and core constructions involving more widely dispersed fuel are permissible.

In terms of power density, a representative gas-cooled core, five feet in diameter and five feet high (2780 liters), would be expected to have a power density of about 32 kw/liter as compared with ranges of 30-40 kw/liter for pressurized water reactors.

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VI. Tables and Sketches

FIG. 1a

GAS-COOLED REACTOR DATA

1	NAME	CALDER HALL ONE REACTOR	HINKLEY POINT ONE REACTOR	GCR-2	EXPERIMENTAL GAS COOLED REACTOR FOR ORNL	PHILADELPHIA ELECTRIC CO. GAS COOLED (CORE NO. 2)	GAS COOLED MARITIME He	GAS COOLED MARITIME CO_2	GAS COOLED MARITIME CO_2 Zr.H
2	REPORT NUMBER			ORNL-2500 [111]	IDO-24027 [68] IDO-24028	GA 593 [42]	GA 1030 [45] GA 1265 GA 1280	GA 570 [41]	GA 570 [41]
3	DESIGNER	U.K.A.E.A.	ENGLISH ELEC., ETC.	ORNL	KAISER- AC	GENERAL ATOMIC	GENERAL ATOMIC	GENERAL ATOMIC	GENERAL ATOMIC
4	PURPOSE	Pu PROD. & POWER	POWER	POWER	PROTOTYPE POWER	PROTOTYPE POWER	PROTOTYPE SHIP PROPULSION	PROTOTYPE SHIP PROPULSION	PROTOTYPE SHIP PROPULSION
5	STATUS	OPERATING	UNDER CONSTRUCTION	CONCEPTUAL	AUTHORIZED	AUTHORIZED	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL
6	COMPLETION DATE	1956	1960-61	NO CONSTRUCTION PLANS	1962-63	1963	R & D		
7	CYCLE	INDIRECT	INDIRECT	INDIRECT	INDIRECT	INDIRECT	DIRECT	DIRECT	DIRECT
8	POWER MWt MWe	182 42	980 250	700 225	84.3 25.7	115 40	53.3 17.5	45.9 14.9	45.0 14.9
9	COOLANT	CO_2	CO_2	He	He	He	He	CO_2	CO_2
10	MODERATOR	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	BeO	S.S. CLAD GRAPHITE	S.S. CLAD Zr $H_{1.6}$
11	REFLECTOR	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	BeO	S.S. CLAD GRAPHITE	S.S. CLAD Zr $H_{1.6}$
12	FUEL	U METAL	U METAL	UO_2	UO_2	UC & ThC IN GRAPHITE	UO_2 IN OXIDE MATRIX	UO_2 IN OXIDE MATRIX	UO_2 IN OXIDE MATRIX
13	FUEL ENRICHMENT %	NATURAL	NATURAL	1.83-2.00	2.2	16.0	20.0	27.1	5.75
14	CLADDING MATERIAL	MAGNOX Mg.	Al2 MAGNOX Mg.	304 S.S.	304 S.S.	GRAPHITE	316 S.S.	316 S.S.	316 S.S.
15	CLADDING SIZE	630" O.D.x.072"T x39" L FINNED		.800" O.D.x .020"Tx37.5 L	.750" O.D. x .020"Tx 29"L	4.15"O.D. x 3.14" I.D.x90" L.	.375 O.D.	.250" O.D. x .012" T.	.250" O.D.x .010" T.
16	CORE DIAMETER - FT.	31	49	30	16	9	6.37	6.37	4.00
17	CORE LENGTH - FT.	21	25	20	19	7.5	6.37	6.37	4.00
18	CORE VOLUME - FT.^{3}	15850	47100	14150	1400	476	203	203	LESS REFL. 50.26
19	CORE VOLUME - LITERS	448872	133387	400730	39025	13480	5749	5749	1423
20	POWER DENSITY - TKW/FT^3	11	20	50	61.17	242	267	226	895
21	HEAT FLUX - BTU/HR./FT.^{2}	60507		56000	66833	87441	55340	56200	106700
22	HEAT TRANSFER AREA - FT.^{2}	10266		45050	4305	4490	3287	2780	1460
23	GAS INLET - TEMP. °F PRESSURE G.	284 100	324 185	450 285	510 300	662 294	753	847 956	800 1877
24	GAS OUTLET - TEMP. °F PRESSURE G.	636 94.5	707	1000 278.4	1050 292	1382	1300 760	1300 851	1300 1764
25	MASS - LBS-HR FLOW - FT^3/MIN.	424.224×10^6	216.0×10^6	209.952×10^6	4.27×10^5	4.8×10^5 $.728 \times 10^5$	27.0×10^4	71.172×10^6	61.5384×10^6
26	CORE VELOCITY - FPS							131	110
27	MAX. MODERATOR TEMP. °F	750	840	1020	1080	> 2200		1400	1000
28	STEAM TO - °F TURBINE - PSIA	590 200	655.2 640.0	950 950	900 1265	1005 1500			
29	AVERAGE FUEL SURFACE TEMP. °F	766.4	820	1200	1300	2400	1500 MAX.	1500 MAX.	1500 MAX.
30	PRESSURE VESSEL SIZE-D.xT.xH-FT.	41x2"x70	73 SPHERE x 3"T	50 SPHEREx3.25" T.	20.66 x4" x46.33	14.33x2"x 34.5		10.4x5.75"x 21.1	7.28x7.44"x 15.0
31	PRESSURE VESSEL MATERIAL	STEEL	STEEL	STEEL SA212-B	STEEL - CARBON	STEEL SA212-B	STEEL SA.302.B	STEEL & S.S. SA-301-B	STEEL SA302-B
32	CONTROL NO. REQ. RODS MAT.	104 BORON S.S.		61 SILVER	29 B4C-S.S.CLAD	46 B4C+CIN S.S.	16 TO 32 RARE EARTH IN S.S.	23 RARE EARTH IN S.S.	39 BORATED S.S.
33	CONTROL MECH.	MOTOR & WINCH		TUBULAR - ELEC & PNEUMATIC	WINCH TYPE	COMB. HYDRO. MECH., PNEU.		MAGNETIC JACK	MAGNETIC JACK
34	THERMAL - THICK. SHIELD - MAT.	1-6" THICK STEEL		1-50 BORO-SILICATE GLASS	1-1" THICK S.S.	3-1" THICK CARBON STL		1"-2"-3" THICK 316-L S.S.	2-1" THICK BORATED S.S.
35	CORE LOADING - KG.	132.3 KG NAT. U	414.5 KG NAT. U	3.016 KG U^{235} 147.784 KG U^{238}	1200 KG OF UO_2	190KG U^{235} 1190 KG Th^{232}	151 KG U^{235} 2250 KG U^{238}	146.6 KG U^{235} 400 KG U^{238}	94 KG U^{235} 1636 KG U^{238}
36	BURNUP OR REFUEL PERIOD - MONTHS			52		38	52	14.5	18.08
37	AVERAGE THERMAL NEUTRON FLUX			5×10^{12}		2.75×10^{13}		1.4×10^{13}	2.7×10^{13}
38	PUMPING POWER - KW.			18300	5300	3729			
39	UNIT POWER COST MILLS/KWH	17.9 IN USA 7.7 IN UK		10.36	33.6				
40	CAPITAL COST $/KW -ELECTRIC	1060 IN USA 660 IN UK		482.87	956.66				
41									
42		A	B	C	D	E	F	G	H

1	NAME	GAS COOLED MARITIME CO_2 H_2O	FLORIDA GAS COOLED PROTOTYPE PRESSURE TUBE	PEBBLE BED REACTOR STEAM POWER PLANT	CLOSED CYCLE REACTOR	TURRET EXPERIMENT	GAS COOLED REACTOR	FLOWABLE SOLIDS REACTOR	DUPONT He GAS COOLED PRESSURE TUBE REACTOR	NAME	1
2	REPORT NUMBER	GA 570 [41]	TID 7564 [133]	NY08753 [110] NY02373 [109]	FICO 101 [35]	LA 2303 [90]	AECU3559 [1]	FLR-1 [38]	DP307 [34]	REPORT NUMBER	2
3	DESIGNER	GENERAL ATOMIC	GENERAL NUCLEAR ENG.	SANDERSON & PORTER	FORD INSTRUMENT CO.	LOS ALAMOS	STUDEBAKER PACKARD	FLUOR CORP.	E.I. DuPONT deNEMOURS CO.	DESIGNER	3
4	PURPOSE	PROTOTYPE SHIP PROPULSION	PROTOTYPE POWER	POWER & U233 BREEDING	POWER	HIGH TEMPERATURE STUDY	POWER STUDY	POWER STUDY	EVALUATION STUDY	PURPOSE	4
5	STATUS	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	PRELIM.	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	STATUS	5
6	COMPLETION DATE		R & D	R & D	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	COMPLETION DATE	6
7	CYCLE	DIRECT	INDIRECT	INDIRECT	DIRECT	HEAT SINK	OPEN CYCLE INDIRECT	INDIRECT	INDIRECT	CYCLE	7
8	POWER MWt MWe	47.5 14.9	173 53	337 125	44 15	3 -	60 17	320.0 99.2	313.0 100.0	POWER MWt MWe	8
9	COOLANT	CO_2	CO_2	He	N_2	He	He	NONE He ATMOSPH.	He	COOLANT	9
10	MODERATOR	H_2O IN AN AL. TANK	D_2O	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	D_2O	MODERATOR	10
11	REFLECTOR	H_2O IN AN AL. TANK	D_2O	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	D_2O	REFLECTOR	11
12	FUEL	UO_2 IN OXIDE MATRIX	UO_2	UO_2 & ThO IN GRAPHITE BALL	UO_2	U^{235} IN GRAPHITE	UC + C	UO_2 GRANULES	NATURAL URANIUM	FUEL	12
13	FUEL ENRICHMENT %	6.00	1.84		10.0		25.0	0.98	-	FUEL ENRICHMENT %	13
14	CLADDING MATERIAL	316 S.S.	S.S.	NONE	316 S.S.	NONE	NONE	NONE	Zr	CLADDING MATERIAL	14
15	CLADDING SIZE	.250" O.D.x .010" T.	.570" O.D. x .015" T.	1.5" DIA. GRAPHITE BALL	.257" O.D.x010" T.x48"L				RIBBON TYPE .508" W x.090"T.x.010" CLAD	CLADDING SIZE	15
16	CORE DIAMETER - FT.	4.33	10	9	5.3	1.04 I.D.x6.16 O.D.	3.33 I.D. x 5.0 O.D.	18	13.84	CORE DIAMETER - FT.	16
17	CORE LENGTH - FT.	4.00	12	8.1	4.0	3.33	4.0	20	13.84	CORE LENGTH - FT.	17
18	CORE VOLUME - FT.^{3}	LESS REFL. 58.92	947	513	88.25			5089	2082	CORE VOLUME - FT.^{3}	18
19	CORE VOLUME - LITERS	1669	26819	14528	2499			144120	58962	CORE VOLUME - LITERS	19
20	POWER DENSITY - TKW/FT^3	806	183	680	498.6		1302	159	150.3	POWER DENSITY - TKW/FT^3	20
21	HEAT FLUX - BTU/HR./FT.^{2}	100000	95300		110000		155000		63846	HEAT FLUX - BTU/HR./FT.^{2}	21
22	HEAT TRANSFER AREA - FT.^{2}	1620			1342		1320		32630	HEAT TRANSFER AREA - FT.^{2}	22
23	GAS INLET - TEMP. °F PRESSURE G.	798 1877	500 513.2	500 1015	760 535	1600	1240	700 FUEL TEMP.	437.0 402.7	GAS INLET - TEMP °F PRESSURE G	23
24	GAS OUTLET - TEMP. °F PRESSURE G.	1300 1765	1050 500	1200 1000	1300 525	2400 500	1740 294	2000 FUEL TEMP.	1052.0 400.0	GAS OUTLET - TEMP. °F - PRESS. G	24
25	MASS - LBS-HR FLOW - FT^3/MIN.	65.9664×10^6		1.36×10^6	1.1×10^6			9.2×10^6	1.526×10^6	MASS - LBS/HR. FLOW - FT^3/MIN.	25
26	CORE VELOCITY - FPS	116	112.5		150			2	103	CORE VELOCITY - FPS	26
27	MAX. MODERATOR TEMP. °F	175	200	>2500			2420	3000	122	MAX. MODERATOR TEMP. °F	27
28	STEAM TO - °F TURBINE - PSIA			1000 1450				850 900	887 1422	STEAM TO - °F TURBINE - PSIA	28
29	AVERAGE FUEL SURFACE TEMP. °F	1500 MAX.	1500	2500	1500 MAX.				1200 MAX.	AVERAGE FUEL SURFACE TEMP. °F	29
30	PRESSURE VESSEL SIZE-D.xT.xH-FT.	7.43x7.58"x 16.7		13.75x5.5"x 21.0	9.0x2"x15.0				16.45x2.85" x37.8	PRESSURE VESSEL SIZE-D-xT-xH-FT.	30
31	PRESSURE VESSEL MATERIAL	STEEL SA-301-B		STEEL SA-212-B	STEEL	STEEL SA-212	INCONEL	STEEL	STEEL	PRESSURE VESSEL MATERIAL	31
32	CONTROL NO. REQ. RODS MAT.	125 RARE EARTH IN S.S.	24	12 HAYNES 25	7 UNCERTAIN	9 B4C IN STEEL		UNCERTAIN	23 CADMIUM	CONTROL NO. REQ. RODS - MAT.	32
33	CONTROL MECH.	MAGNETIC JACK		ELECTRIC RACK & PINION	ELECTRIC RACK & PINION				NOT LISTED	CONTROL MECH.	33
34	THERMAL - THICK. SHIELD - MAT.	1-.5",1-1"T. 316 S.S.		1-2" THICK STEEL	3-2" THICK STEEL	STEEL			1-1" THICK BORATED S.S.	THERMAL - THICK. SHIELD - MAT.	34
35	CORE LOADING - KG.	108.5 KG U^{235} 1808.5 KG U^{238}	174 TONS UO_2	90.2 KG U^{233} 992.2 KG $TH.^{232}$	76.2 KG U^{235} 861 KG U^{238}			174 TONS UO_2	48-4 TONS NAT. URANIUM	CORE LOADING - KG.	35
36	BURNUP OR REFUEL PERIOD - MONTHS	21.34		UNCERTAIN	12.00			240	15.25	BURNUP OR REFUEL PERIOD - MONTHS	36
37	AVERAGE THERMAL NEUTRON FLUX	1.25×10^{13}		1.3 TO 2.2×10^{14}	1.28×10^{13}					AVERAGE THERMAL NEUTRON FLUX	37
38	PUMPING POWER - KW.			8526	28.8				5233	PUMPING POWER - KW.	38
39	UNIT POWER COST MILLS/KWH			8.07	15.08			6.93	20.959	UNIT POWER COST MILLS/KWH	39
40	CAPITAL COST $/KW -ELECTRIC			254.00	385.00			222.60	769.23	CAPITAL COST $/KW -ELECTRIC	40
41											41
42		J	K	L	M	N	O	P	R		42

GAS-COOLED REACTOR DATA

						ARMY GAS COOLED REACTOR PROGRAM													
1	NAME	DuPONT H_2 GAS COOLED PRESSURE TUBE REACTOR	DuPONT CO_2 GAS COOLED PRESSURE TUBE REACTOR	NUCLEAR GAS ENGINE NGE-1	TURRET HIGH TEMPERATURE GAS CYCLE REACTOR	GCRE-1-H_2O MODERATED HETROGENEOUS	GCRE-2 GRAPHITE MODERATED HOMOGENEOUS	ML-1 MOBILE LOW POWER	GAS TURBINE TEST FACILITY	DUST FUELED REACTOR	GAS COOLED REACTOR POWER PLANT	CLOSED CYCLE GAS TURBINE POWER PLANT	GAS COOLED GRAPHITE UO_2 POWER REACTOR	ARGONNE He COOLED POWER REACTOR	G.M.C. MARINE REACTOR	MARINE GAS COOLED REACTOR	CLOSED CYCLE GAS TURBINE POWER PLANT ETC.	NAME	1
2	REPORT NUMBER	DP 307 [34]	DP 307 [34]	CF58-9-12 [30]	LA2198 [89]	IDO-28506 [75]	IDO-28515 [81]	IDO-28537 [83]	INP-6467 [106]	AECU 3909 [2]	WKNL-46 [139]	ATC-54-12 [15]	REPRINT DATED MARCH 1955 [147]	TID-2506 [130]	TID-5510 [131]	ASAE-S5 [14]	PROPOSAL TO AEC [148]	REPORT NUMBER	2
3	DESIGNER	E.I.DuPONT deNEMOIRS CO.	E.I.DuPONT deNEMOIRS CO.	ORNL	LOS ALAMOS	AERO-JET GENERAL	AERO-JET GENERAL	AERO-JET GENERAL	AERO-JET GENERAL	ARMOUR RESEARCH	WALTER KIDDE LABS.	AMERICAN TURBINE CO.	FARRINGTON DANIELS	ARGONNE NATIONAL LAB.	GENERAL MOTORS	AMERICAN STANDARD	JACKSON & MORELAND	DESIGNER	3
4	PURPOSE	EVALUATION STUDY	EVALUATION STUDY	POWER STUDY	POWER STUDY	EXPERIMENT POWER				POWER STUDY	POWER STUDY	POWER STUDY	POWER STUDY	POWER STUDY	POWER STUDY	MARINE POWER STUDY	POWER STUDY	PURPOSE	4
5	STATUS	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	UNDER CONSTRUCTION				CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	STATUS	5
6	COMPLETION DATE	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	1961				NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	COMPLETION DATE	6
7	CYCLE	INDIRECT	INDIRECT	RECIPROCATING ENGINE	DIRECT	DIRECT				INDIRECT	DIRECT	DIRECT	CLOSED CYCLE INDIRECT	DIRECT	DIRECT	DIRECT AND STEAM	DIRECT	CYCLE	7
8	POWER MWt MWe	377.4 100.0	440.0 100.0	60.0 18.0	66.0 20.0	2.2 -				500 --	1.112 .100 ELEC. .400 HEAT	148.5 60.0	- 2.0	189.0 61.4	55.0 16.39	53.0 15.0	1000 300	POWER MWt MWe	8
9	COOLANT	H_2	CO_2	DRY N_2	N_2	N_2				He	He	He	He TO AIR	He	He	He	CO_2	COOLANT	9
10	MODERATOR	D_2O	D_2O	GRAPHITE	GRAPHITE	H_2O				GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	H_2O	MODERATOR	10
11	REFLECTOR	D_2O	D_2O	GRAPHITE	GRAPHITE	H_2O				GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	H_2O	REFLECTOR	11
12	FUEL	NATURAL URANIUM	NATURAL URANIUM	UO_2	ENRICHED U	UO_2 IN 316 SS				ENRICHED UC	ENRICHED UO_2 IN S.S.	ENRICHED	UO_2 IN GRAPHITE	ENRICHED U^{233} IN TH.	UO_2	ENRICHED UO_2	ENRICHED UO_2	FUEL	12
13	FUEL ENRICHMENT %	-	-	3.0	90.0	30.0				93.0	93.4			3.47	100	4.0	3.0	FUEL ENRICHMENT %	13
14	CLADDING MATERIAL	MG.	MG.	S.S.	GRAPHITE	318. S.S.				NONE	S.S.			S.S.		S.S.	S.S	CLADDING MATERIAL	14
15	CLADDING SIZE	RIBBON TYPE .058"W.x.090"T x.010 CLAD	RIBBON TYPE .508"Wx.090" x .010" CLAD	.80"O.D.x.032"T x24" L.	.75" O.D.x .25"Tx6.0" L.	COAXIAL TUBES .045"T.				-	COAXIAL RINGS .036"T.x.008" CLAD.			.375" O.D.x .010"T.x96" L.		ANNULAR RINGS	1.3" O.D.x 144" L.	CLADDING SIZE	15
16	CORE DIAMETER -FT.	13.84	14.56	8.5	9.0	2				6	4			8		7.92	9.0	CORE DIAMETER - FT.	16
17	CORE LENGTH - FT	13.84	13.84	10.0	6.5	2.33				10	4			8		7.92	12.0	CORE LENGTH - FT.	17
18	CORE VOLUME - FT.^{3}	2082	2304		413.5					282	50.26			402		391	764	CORE VOLUME - FT.^{3}	18
19	CORE VOLUME - LITERS	58962	65249		11710					7986	1423			11385		11073	21636	CORE VOLUME - LITERS	19
20	POWER DENSITY- TKW/FT^3	181.3	191.0		159.6	300				63	22.12			470		135.5	1310	POWER DENSITY -TKW/FT^3	20
21	HEAT FLUX -BTU/HR/FT^2	77940	61200		136578	33160					21700			227000		82260	282020	HEAT FLUX -BTU/HR/FT^2	21
22	HEAT TRANSFER AREA - FT^2	32630	46000		1649.3	214.1					167.3			2835			12102	HEAT TRANSFER AREA - FT^2	22
23	GAS INLET TEMP. °F PRESSURE G	437.0 403.0	356.0 616.3	600 1500	727 530	800 210				1000 441	865.5 164	886.0 1000		886.0 1015	768 1000	783 970	745 1180	GAS INLET TEMP. °F PRESSURE G	23
24	GAS OUTLET TEMP. °F PRESSURE G	714.2 400.0	689.0 600.0	1100 1456	1300 520	1200 197				2500 -	1150.0 161	1400 985		1400 997	1300	1300 940	1400 1080	GAS OUTLET TEMP. °F PRESSURE G	24
25	MASS FLOW LBS-HR FT^3/MIN.	1.197×10^6	15.94×10^6	10.04×10^6 7530	1.48×10^6	6.3×10^4					10240	$.79\times10^6$ 47220		1.002×10^6 72025		2.798×10^6	1123.2×10^6	MASS FLOW LBS/HR FT^3/MIN.	25
26	CORE VELOCITY - FPS	147	64.5	90		190				220	221			300		231		CORE VELOCITY - FPS	26
27	MAX.MODERATOR TEMP. °F	122	122								1190							MAX.MODERATOR TEMP. °F	27
28	STEAM TO TURBINE °F PSIA	671 485	637 375			HEAT SINK												STEAM TO TURBINE °F - PSIA	28
29	AVERAGE FUEL SURFACE TEMP. °F	856 MAX.	855 MAX.			1650 MAX.					1217			1600		1596		AVERAGE FUEL SURFACE TEMP. °F	29
30	PRESSURE VESSEL SIZE -DxTxH-FT.	16.45x2.85" x37.8	17.16x4.59" x38.	14.0x8"x 23.0		PRESSURE TUBES					6.0x1 1/4" x 10.33			14.3x3.5" x28		11.92x5"T x32.5	12.82x5" x20.83	PRESSURE VESSEL SIZE -DxTxH-FT.	30
31	PRESSURE VESSEL MATERIAL	STL.OR SS CLAD	STEEL	STEEL SA212	STEEL	AL.					STEEL 304 S.S			CARILLOY TI STEEL		SA302-B + SS CLAD		PRESSURE VESSEL MATERIAL	31
32	CONTROL RODS NO.REQ. - MAT.	23 CADMIUM	23 CADMIUM		BORON IN GR.	12 MALLORY ALLOY + Cd.					8 B_4C in S.S.					17 16.2% BORON 1-Hf		CONTROL RODS NO.REQ. - MAT.	32
33	CONTROL MECH.	NOT LISTED	NOT LISTED	ELECTRIC RACK & PINION							RACK & PINION							CONTROL MECH.	33
34	THERMAL SHIELD THICK MAT.	1-1" THICK BORATED S.S.	1-1" THICK BORATED S.S.		STEEL						NONE			2.25",1.5",.75" STEEL		2.1",1.2" S.S.		THERMAL SHIELD THICK. - MAT.	34
35	CORE LOADING - KG	48.4 TONS NAT.URANIUM	52.0 TONS NAT. URANIUM			19.2 KG U^{235}					8.2 KG U^{235}			5429 KG.TH. 195 KG. U^{233}		5510.4 LBS. U^{238} 104KG U^{235}		CORE LOADING - KG	35
36	BURNUP OR REFUEL PERIOD - MONTHS	15.25	19.3			4.1 TO 13.7					-							BURNUP OR REFUEL PERIOD - MONTHS	36
37	AVERAGE THERMAL NEUTRON FLUX					3×10^{12}					2.9×10^{12}			4.5×10^{13}				AVERAGE THERMAL NEUTRON FLUX	37
38	PUMPING POWER KW.	6148	8318											4252				PUMPING POWER KW.	38
39	UNIT POWER COST MILLS/KWH	22.674	24.486														8.6	UNIT POWER COST MILLS/KWH	39
40	CAPITAL COST $/KW - ELECTRIC	842.55	914.32														177.0	CAPITAL COST $/KW - ELECTRIC	40
41																			41
42		S	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG	AH		42

FIG. 1c

GAS-COOLED REACTOR DATA

1	NAME	EXPERIMENTAL REACTOR FOR HIGH OPERATING TEMPERATURE	GAS COOLED REACTOR	GAS COOLED LIQUID METAL REACTOR	THE HOT GAS COOLED REACTOR NO. 1 HGCR-1	STEAM COOLED PRESSURE TUBE REACTOR U.K.	GAS SUSPENSION REACTOR EXPERIMENT	DIRECT CYCLE STEAM COOLED REACTOR FOR SHIP PROPULSION	"DRAGON" PROJECT									NAME	1
2	REPORT NUMBER	NDA64-101 [103]	HW54727 [64]	TID 2506 P.125-141 [129]	ORNL 2653 [114]	Y113 [142]	BAW 1159 [18]	ORNL 2759 [118]	145 NP 9161 [153]									REPORT NUMBER	2
3	DESIGNER	NUCLEAR DEVELOPMENT CO.	GENERAL ELECTRIC CO. HAPO	B.N.L.	O.R.N.L.	VICKERS NUCLEAR ENG.	BABCOCK & WILCOX	ORNL	UKAEA									DESIGNER	3
4	PURPOSE	PROCESS STUDY	POWER STUDY	POWER STUDY	POWER STUDY	POWER STUDY	POWER STUDY	POWER STUDY	POWER STUDY									PURPOSE	4
5	STATUS	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	CONCEPTUAL	UNDER CONSTRUCTION									STATUS	5
6	COMPLETION DATE	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS	NO CONSTRUCTION PLANS										COMPLETION DATE	6
7	CYCLE	TWO ZONE He & H_2O	DIRECT	DIRECT	INDIRECT	INDIRECT	INDIRECT	DIRECT	DIRECT									CYCLE	7
8	POWER - MWt / MWe	15 / -	1000.0	148.5 / 60.0	3095.0 / 1130.0	150.0	800	73 / 15.7	20.0									POWER - MWt / MWe	8
9	COOLANT	He & H_2O	He	He	He	STEAM	N_2 + GRAPHITE POWDER	STEAM	HE									COOLANT	9
10	MODERATOR	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	D_2O	GRAPHITE	H_2O	BEO									MODERATOR	10
11	REFLECTOR	GRAPHITE	GRAPHITE	GRAPHITE	GRAPHITE	H_2O	GRAPHITE	BeO (AL. CLAD)+ H_2O	GRAPHITE									REFLECTOR	11
12	FUEL		ENRICHED UO_2	URANIUM IN BISMUTH	UO_2 IN GRAPHITE	UO_2	UC	UO_2	U&TH									FUEL	12
13	FUEL ENRICHMENT %		1.25		2.0	1.7	2.0	2.2										FUEL ENRICHMENT %	13
14	CLADDING MATERIAL	GRAPHITE	S.S.		NONE	S.S.	SS, Zr, OR Be	S.S.										CLADDING MATERIAL	14
15	CLADDING SIZE	17.5" O.D.x72"L			-			.750"x.020" x42"										CLADDING SIZE	15
16	CORE DIAMETER-FT			5' CUBE	30	10		3.6	3.52									CORE DIAMETER- FT	16
17	CORE LENGTH - FT			5' CUBE	20	10	25	10	5.25									CORE LENGTH - FT	17
18	CORE VOLUME - FT^3			25	14137.2			101	51									CORE VOLUME - FT^3	18
19	CORE VOLUME - LITERS			708	400365.5			2850	1444									CORE VOLUME - LITERS	19
20	POWER DENSITY - TKW/FT^3			5940	218.93			722	396.48									POWER DENSITY - TKW/FT^3	20
21	HEAT FLUX - BTU/HR/FT^2				245000	.		15800	76093									HEAT FLUX - BTU/HR/FT^2	21
22	HEAT TRANSFER AREA - FT^2																	HEAT TRANSFER AREA - FT^2	22
23	GAS INLET TEMP °F / PRESSURE G	1000 / 135		886	525	500	473 / 165	525 / 880	662									GAS INLET TEMP °F / PRESSURE G	23
24	GAS OUTLET TEMP °F / PRESSURE G	2500	1300	1400 / 1000	1500 / 300	970 / 585	1000 / 97	860 / 860	1382 / 294									GAS OUTLET TEMP °F / PRESSURE G	24
25	MASS FLOW LBS/HR / FT^3/MIN.	16000 He ONLY			518.4×10^6	1.74×10^6	15.26×10^6	$.964 \times 10^6$	76.348×10^3									MASS FLOW LBS/HR / FT^3/MIN	25
26	CORE VELOCITY - FPS	126 He ONLY				180		131										CORE VELOCITY FPS	26
27	MAX. MODERATOR TEMP. °F				1100	194												MAX. MODERATOR TEMP. °F	27
28	STEAM TO TURBINE - °F / PSIA				1050 / 1450	800 / 435		850 / 880										STEAM TO TURBINE - °F / PSIA	28
29	AVERAGE FUEL SURFACE TEMP. °F			1800	2000	1256	1070	1200	2462									AVERAGE FUEL SURFACE TEMP. °F	29
30	PRESSURE VESSEL SIZE-DxT.xH -FT	OUTER 12x1.5" x15.5		14.75 SPHERE x3.75"T	50' SPHERE x3.25"T.			6x2"x18	11.5x2.25 x58									PRESSURE VESSEL SIZE-DxT.xH -FT	30
31	PRESSURE VESSEL MATERIAL	AL OUTER S.S. INNER		ALLOY STEEL ASTM A204	STEEL SA212.8			CARBON STEEL & S.S. CLAD										PRESSURE VESSEL MATERIAL	31
32	CONTROL RODS NO. REQ. / - MAT.	14 / 1% BORON STL.			61 / SILVER				24 / B4C									CONTROL RODS NO. REQ. / - MAT.	32
33	CONTROL MECH.	RACK & PINION							RACK & PINION									CONTROL MECH.	33
34	THERMAL SHIELD - THICK. / MAT.	24"T. BORATED GRAPHITE			1-.5" T BORON GLASS													THERMAL SHIELD - THICK. / MAT.	34
35	CORE LOADING - KG.	CA-32 KG U_{235}																CORE LOADING - KG	35
36	BURNUP OR REFUEL PERIOD -MONTHS																	BURNUP OR REFUEL PERIOD - MONTHS	36
37	AVERAGE THERMAL NEUTRON FLUX	1.2×10^{13} LOW ZONE			4×10^{13}													AVERAGE THERMAL NEUTRON FLUX	37
38	PUMPING POWER - KW				53690			1120										PUMPING POWER - KW	38
39	UNIT POWER COST MILLS-KWH				7.8													UNIT POWER COST MILLS/KWH	39
40	CAPITAL COST $ /KW/ELECTRIC				220													CAPITAL COST $ /KW-ELECTRIC	40
41																			41
42		AJ	AK	AL	AM	AN	AO	AP	AR										42

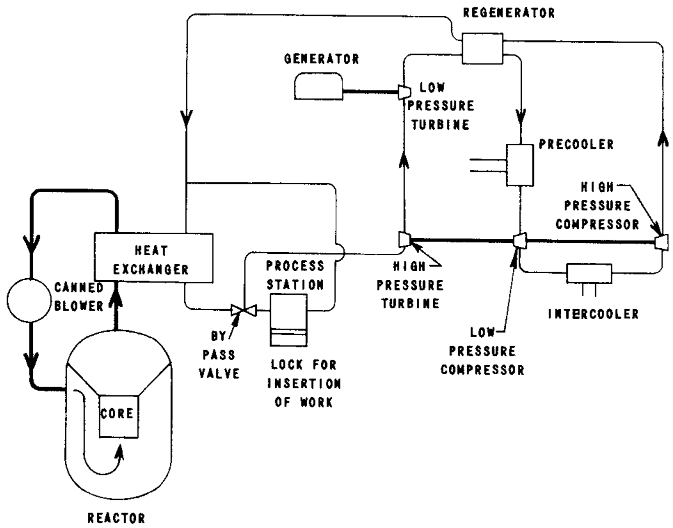


FIG. 2A
REACTOR FLOW SHEET WITH GAS TO HEAT EXCHANGER, WITH PROCESS STATION AND CLOSED DIRECT CYCLE AIR TURBINE.

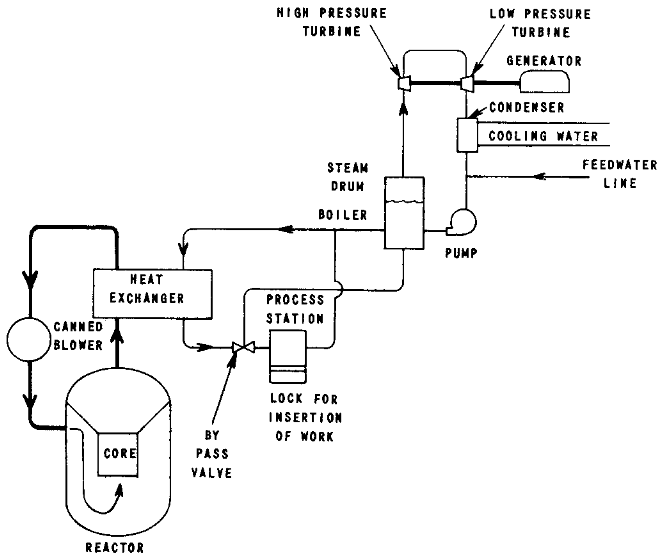


FIG. 2B
REACTOR FLOW SHEET WITH GAS TO AIR HEAT EXCHANGER, WITH PROCESS STATION, AND AIR TO WATER BOILER AND STEAM TURBINE CYCLE.

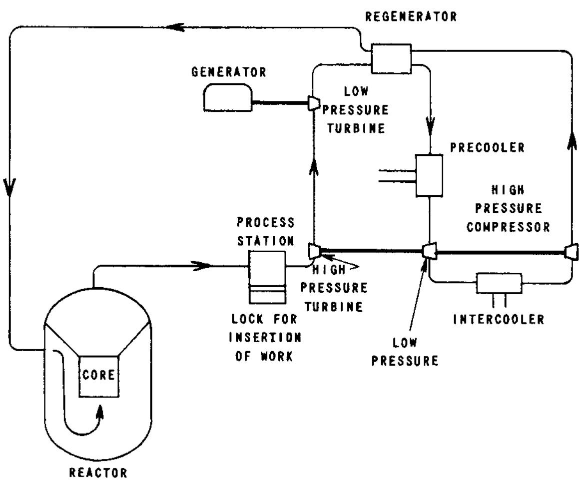


FIG. 2C
REACTOR FLOW SHEET WITH GAS TO PROCESS STATION AND ONTO CLOSED DIRECT CYCLE GAS TURBINE.

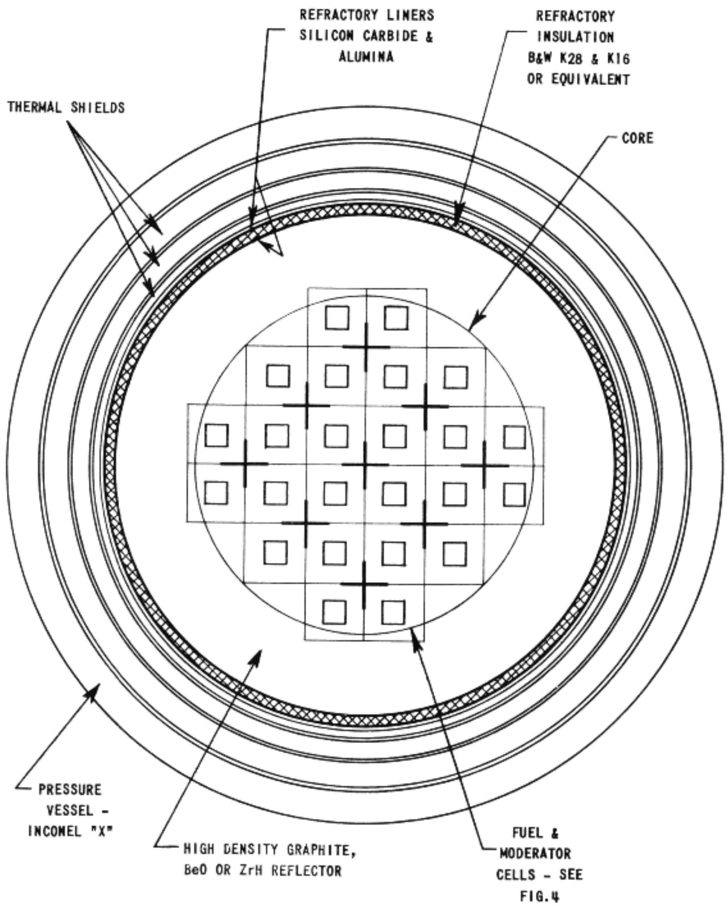


FIG. 3

A TYPICAL REACTOR CROSS SECTION
SHOWING POSSIBLE FUEL ARRANGEMENT

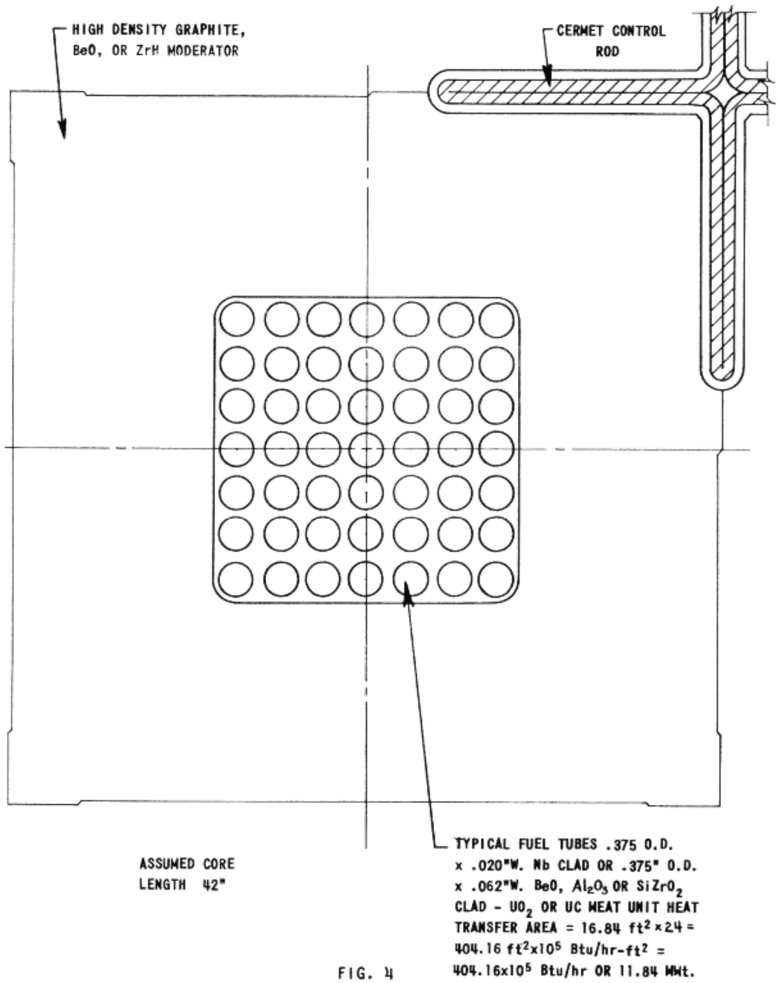
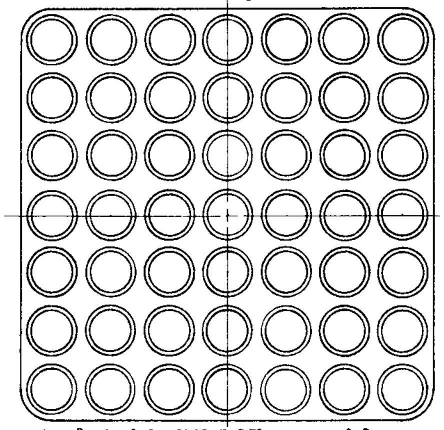


FIG. 4

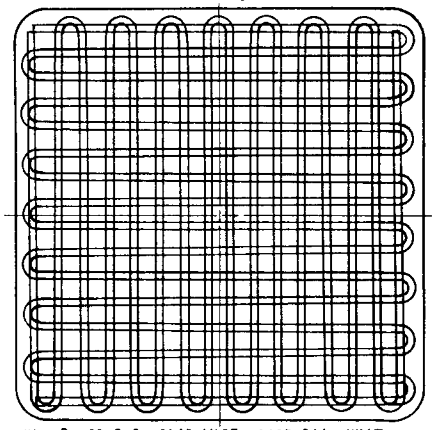
A TYPICAL FUEL & MODERATOR CELL

FIG. 5A



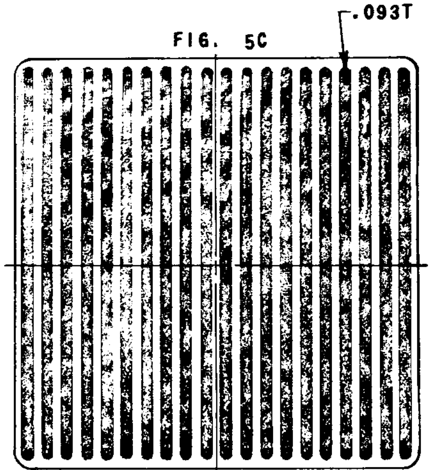
Nb, Be OR S.S. CLAD TUBES - .375" O.D. x .048" WALL - UNIT HEAT TRANSFER = 29.36 ft^2 x 24 = 705 ft^2 x 10^5 BTU/hr - ft^2 = 705 x 10^5 BTU/hr OR 20.66 MWt.

FIG. 5B



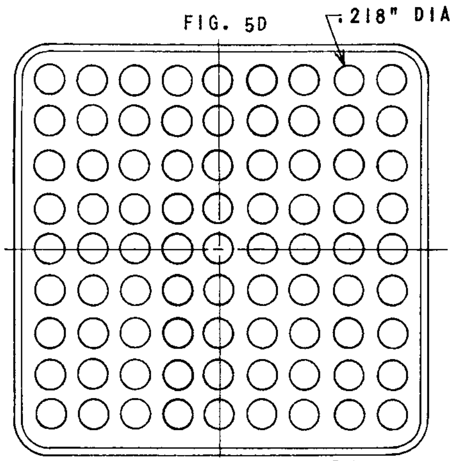
Nb, Be OR S.S. CLAD WIRE .062" DIA. UNIT HEAT TRANSFER = 57.64 ft^2 x 24 = 1383.4 ft^2 x 10^5 BTU/hr - ft^2 = 1383.4 x 10^5 BTU/hr OR 40.53 MWt

FIG. 5C



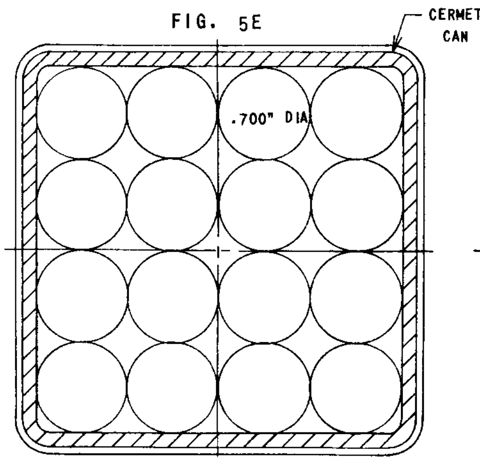
UO_2 OR UC IN MATRIX OF BeO, $SiZrO_2$ OR Al_2O_3 - PLATES - UNIT HEAT TRANSFER = 35.77 ft^2 x 24 = 858.5 ft^2 x 10^5 BTU/hr-ft^2 = 858.5 x 10^5 BTU/hr OR 25.15 MWt

FIG. 5D



UO_2 OR UC PLACQUES WITH GRAPHITE, BeO, $SiZrO_2$ OR Al_2O_3 MATRIX. .093"T x .062" SPACE, STACKED. UNIT HEAT TRANSFER = 34.9 ft^2 x 24 = 837.6 ft^2 x 10^5 BTU/hr-ft^2 = 837.6 x 10^5 BTU/hr-ft^2 = 837.6x10^5 BTU/hr OR 24.54 MWt

FIG. 5E



SAME MATERIAL AS 4E-BALLS LOADED IN CERMET CAN. UNIT HEAT TRANSFER AREA = 9.3 ft^2 x 24 = 223.2 ft^2 x 10^5 BTU/hr-ft^2 = 223.2 x 10^5 BTU/hr OR 6.54 MWt

FIG. 5F

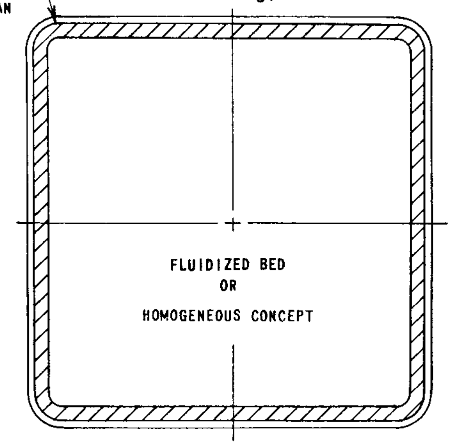


FIG. 5
POSSIBLE FUEL ARRANGEMENTS

FIGURE 6

PROPERTIES OF MATERIALS FOR MODERATORS AND REFLECTORS

	AGOT Graphite	TSF Graphite	Beryllium	Beryllium Oxide	Water	Heavy Water
Atomic Weight	12.011	12.011	9.013	25.02	18.016	20.030
Density (g/cm^3)	1.70	1.70	1.85	3.025	1.00	1.10
Microscopic absorption cross section (millibarns)*	4.50	3.95	10.0	10.0	660	1.0
Microscopic scattering cross section (barns)*	5.09	5.09	7.0	6.8	103	13.6
Macroscopic absorption cross section ($cm \times 10^5$)	38.30	33.67	124	73	2200	3.30
Macroscopic scattering cross section (cm)	0.432	0.432	0.865	0.501	3.45	0.449
Average logarithmic energy decrement per collision	0.158	0.158	0.209	0.173	0.948	0.570
Slowing-down power	0.0684	0.0684	0.181	0.087	3.27	0.256
Moderating Ratio	177.5	203	146	119	148	7750
Reflecting Ratio	1125	1285	698	686	157	13600
Diffusion length	49	52	22	32	2.73	116

*at 2200 meters/sec

FIG. 7

TABLE I (FROM HW 54727-II-3)
GAS COOLANT & BARE FUEL ELEMENT COMPATABILITY
MAX. SURFACE TEMP. °F

GAS		U METAL	U ALLOY	UO_2	UC	UN					
CO_2		778		958							
N_2		868		?	2038	1318					
He	LIMITED BY MELTING TEMPERATURE OF CORE MATERIALS										

TABLE 2 (FROM HW 54727 II-4)
FUEL ELEMENT & CORE JACKET COMBINATIONS
MAX. ALLOWABLE INTERFACE TEMPERATURES WITH NO DIFFUSION BARRIERS - °F

CORE MATERIAL	MAX. CORE TEMP.	Al	Be	Mg	Zr	SS	Ti	Fe	C	Mo	Nb
U METAL	1174	418	1138	1138	1138	1318	958	1138	2038	1138	1138
U ALLOY	2038								2038	–	–
UO_2	3658	958	958	868	1138	1768	1318	1768	3658	–	–
UC	3658	1138	1318	1228	1318	1318	1318	958	3658	–	–
UN	3658	1138	1318	1228	1318	1318	1318	958	3658	–	–

TABLE 3 (FROM HW 54727 II-4)
GAS COOLANT & FUEL ELEMENT JACKET COMPATABILITY
ALLOWABLE OPERATING TEMPERATURES - °F

	CROSS SECTION BARNES	AL	Be	Mg	Zr	SS	Ti	Fe	C	Mo	Nb
CO_2	.003	1138	958	868	1318	1768	–	958	958	–	–
N_2	1.9	1138	958	778	1318	1318	778	868	5458	–	598
He	.007	1138	–	958	1318	1768	–	958	5458	4558	3658
CROSS SECTION		.23	.01	.063	.18	3.0	6.0	2.5	.0032	2.5	1.0

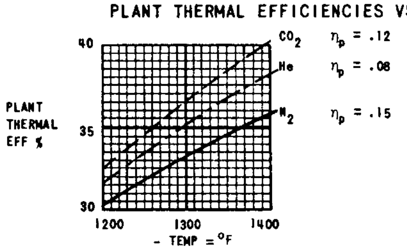
TABLE 4 (FROM HW 54727 V-5)
ORDER OF PREFERANCE FOR GAS COOLANTS

CHEMICAL PROPERTIES	NUCLEAR PROPERTIES	ACTIVATION	DECONTAMINATION	CYCLE EFFICIENCY	GAS RATE	WORK RATIO	PUMPING LOSS HEAT TRANSFER	COST & AVAILIBILITY	EQUIP'T. SIZE	ABSORPTION	DESIGN & OPERATIONAL PROBLEMS
He CO_2 N_2	CO_2 He N_2	He N_2 –	He CO_2 N_2	CO_2 He N_2	He N_2 CO_2	CO_2 N_2 He	CO_2 He N_2	CO_2 N_2 He	N_2 CO_2 He	CO_2 He N_2	CO_2 N_2 He

TABLE 5 (FROM HW 54727 VI-13)
COST & AVAILABILITY OF GASES (STD.TEMP. & PRESSURE)

GAS	He	A *	Ne *	CO_2	H_2	N_2 *				* OBTAINED BY FRACTIONAL DISTILLATION OF AIR	
COST $/ft³	0.015	0.074	42.50	0.003	0.100	0.08					
AVAILABILITY	U.S.A.	0.93 V/O OF AIR	0.0018 V/O OF AIR	WORLD WIDE	WORLD WIDE	78.06 V/O OF AIR					

TABLE 6 (FROM HW 54727 VI7)
PLANT THERMAL EFFICIENCIES VS MAX. CYCLE TEMP. (BASED ON EQUAL REACTOR OUTPUTS)



REACTOR CONDITIONS
POWER LEVEL 500 MW
REACTOR ΔT 500°F
SPECIFIC TUBE POWER 25 KW/ft
LATTICE 8"
$\eta_p = \Delta P/P$ MAX.

RATIO OF POWER PLANT INVESTMENT
He = 1.00
N_2 = 1.00
CO_2 = 1.03

FIG. 8

TABLE 7 (FROM ORNL 2500 PART 2 - P. 6.3)

PROPERTIES OF GASES SUITABLE FOR REACTOR COOLING

GAS	He	N_2	CO_2
MOLECULAR WEIGHT	4	28	44
THERMAL CONDUCTIVITY - Btu/hr-ft^2 °F/ft 700°F 1330°F	 0.135 0.172	 0.028 0.037	 0.028 0.042
VISCOSITY CENTIPOISES 700°F 1330°F	 0.033 0.044	 0.031 0.041	 0.028 0.041
SPECIFIC HEAT - Btu/lb/°F 700°F 1330°F	 1.24 1.24	 0.259 0.279	 0.028 0.041
DENSITY AT S.T.P. lb/ft^3	0.0104	0.0727	0.114
VOLUMETRIC SPECIFIC HEAT AT S.T.P.-Btu/ft^3°F	0.0129	0.0180	0.0238
RELATIVE HEAT TRANSFER COEFFICIENT COMPARED TO He FOR SAME GAS TEMPERATURE AND SAME POWER OUTPUT.	1.00	0.73	0.79
RELATIVE PUMPING POWER COMPARED TO HELIUM FOR SAME GAS TEMPERATURE & SAME POWER OUTPUT	1.00	2.20	0.88
RELATIVE PUMPING POWER COMPARED TO He	1.00	4.00	1.8
COST OF GAS PER 1000 ft^3 AT S.T.P.	22.7	10.0	5.0
RELATIVE TOTAL ACTIVITY	18.5	9294.0	1.0
RELATIVE GAMMA ACTIVITY	0	4.56×10^{-2}	1.0

TABLE 8 (FROM ORNL 2500 PART 2 - P. 6.2)

RELATIVE COOLING PUMPING POWER AS A FUNCTION OF INLET TEMPERATURE

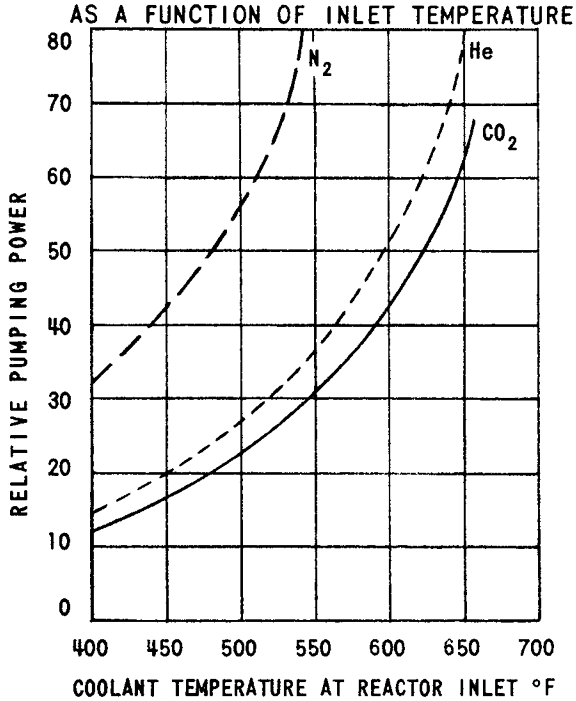


TABLE 9 (FROM ORNL 2510-P.14.5)

HEAT FLUX OBTAINABLE WITH He OR CO_2 (AT 400°F)*

PRESSURE PSIA	$\frac{Q}{A}$ MAX. (Btu/hr-ft^2)
300	100,000 - 200,000
600	175,000 - 350,000
900	250,000 - 500,000
1200	300,000 - 600,000
1500	375,000 - 750,000

* FLUXES WITH H_2 WOULD BE ROUGHLY TWICE THOSE GIVEN, WITH N_2 OR AIR APPROX. 1/2.

FIG. 9

TABLE 10 (FROM GA593-P.109)
COMPOSITION & PHYSICAL PROPERTIES OF SOME POTENTIAL CLADDING MATERIALS

MATERIAL	TYPICAL COMPOSITION (WT. %)	DENSITY	ULTIMATE TENSILE STRENGTH		YIELD STRENGTH		ELONGATION		MODULUS OF ELASTICITY	
			TEMP. (°F)	PSI	TEMP. (°F)	PSI	TEMP. (°F)	%	TEMP. (°F)	PSI x 10^{-6}
AUSTENITIC S.S. TYPE 347	Fe BAL.; Cr.19.0; Ni. 10.0; Mn.2.0; Nb. 0.75.	7.92	70 1300 1500	91000 40000 23000	70 1300 1500	39500 24000 19500	70 1300 1500	45-55 51 76	70 1300 1500	28.0 20.7 19.4
FERRITIC S.S. TYPE 430	Fe BAL.: Cr.17.0; Mn, 1.0.	7.86	70 1300 1500	74000 14000 6500	70 1300	39500 8000	70 1300 1500	20-35 64 83	70	29.0
INCONEL "X"	Ni, 73.0; Cr. 15.0 Nb.0.6; Ti,2.3; AL.0.9; Fe. 6.5	8.3	70 1200 1400	164000 122000 82000	70 1200 1400	92000 82000 65000	70 1200 1500	24 9 22	70 1200 1500	31.0 25.5 23.1
Mo-0.5 TI ALLOY	Mo, BAL., Ti,0.45	10.2	80 1200 1600	132100 100500 88300	80 1200 1600	99100 84000 76500	80 1200	31 17	70 1400	46.0 40.0
Zr. ARC MELTED	Zr, 99+	6.5	75 900	52000 12000					70 600	13.8 10.5
Zr.-5Sn ALLOY	Zr., BAL: Sn.5	6.5	75 900	78000 43000	75 900	71000 29000			75	14.0
Nb	Nb, 99+	8.66	70 1000	35200 28800	70 1000	21000 9400	70 1000	29(49) 24	70	15.1 (24.8)
Nb-Zr ALLOY	Nb, BAL. Zr, 1.0	8.6	70	37600	70	21400	70	18.2		
Nb,10Ti, 10Mo ALLOY	Nb BAL., Mo. 10.0, Ti, 10.0.	8.08	75 1150 1500	100000 70500 63000	75 1150 1500	92000 52000 49000	75 1150 1500	22.0 19.0 5.0	75 1200 1500	16.5 16.5 16.0

TABLE 11 (FROM GA593 P.110)
ATOMIC & THERMAL PROPERTIES OF SOME POTENTIAL CLADDING MATERIALS

MATERIAL	THERMAL NEUTRON CROSS SECTION (cm^{-1})	MELTING POINT (°F)	THERMAL CONDUCTIVITY		COEFFICIENT OF THERMAL EXPANSION		SPECIFIC HEAT	
			TEMP. °F	BTU/hr-ft^2-°F/ft	TEMP. °F	in./in./°F x 10^5	TEMP. °F	BTU/lb-°F
S.S. TYPE 347	0.2607	2575	200 1000	9.2 12.5	32-212 32-1200	9.3 10.6	32-212	0.12
S.S. TYPE 430	0.2279	2715	68-212 930	13.3 15.0	68-212 68-1830	5.8 7.1	32-212	0.11
INCONEL "X"	0.3609	2550-2600	110 1100 1475	7.1 13.1 16.3	200 100-1500	7.7 9.0	77-212	0.11
Mo-0.5 Ti ALLOY	0.160	4730	68 1100	68.2 63.6	68-212 68-1100	3.05 3.23	75	0.06 ARC CAST Mo
Zr. ARC MELTED	0.008		60 575	12.2 10.7	75 1110-1290	5.8 4.9	70 1340	0.069 0.086
Zr - SN ALLOY	0.010	3350	60 575	5.6 6.6	70-660	3.6		
Nb	0.060	4380	32-212 1100	31 37	0-1800	3.8		0.065
Nb-1.0 Zr ALLOY	0.060							
Nb-10-Ti10-Mo ALLOY	2.0	4100	2200	41	0-1800	4.1	70-2000	0.074

TABLE 12 (FROM GA593 P.111)
FABRICATION CHARACTERISTICS, AVAILABILITY & COST OF SOME POTENTIAL CLADDING MATERIALS

MATERIAL	FORMABILITY	MACHINABILITY	WELDABILITY	BRAZABILITY	AVAILABILITY	COMP. COST S.S. #304 = 1.0
S. S. TYPE 347	GOOD	FAIR	GOOD	GOOD	GOOD	1.5
S. S. TYPE 430	GOOD	GOOD	FAIR	GOOD	GOOD	0.9
INCONEL "X"	FAIR TO GOOD	POOR TO FAIR	GOOD	FAIR	FAIR	2.5
Mo AND ITS ALLOYS	POOR (MUST BE FORMED HOT)	POOR	POOR (PROTECTIVE ATMOS.REQ.)	DIFFICULT	FAIR	10+
Zr & Zr.Sn ALLOYS	GOOD	POOR TO GOOD	FAIR	DIFFICULT	LIMITED	50
Nb & ITS ALLOYS	GOOD	GOOD	FAIR TO DIFFICULT		LIMITED	100

FIGURE 10

EXAMPLES OF HIGH TEMPERATURE PROCESSES
(From NDA-64-101, Page 72)(103)

1. Sintering or casting of metals (tungsten 5800°F, silicon 2600°F)
2. Cottrell Process for nitrogen fixation (3700°F - 4000°F)
3. Manufacture of carborundum, calcium carbides, graphite, etc. (3600°F - 4000°F)
4. Manufacture of fused silicon, fused quartz, etc. (3100°F - 3300°F)
5. Manufacture of ceramics and refractory brick (3000°F)
6. Manufacture of ferroalloys, alloy steels, etc. (3000°F)
7. Glass manufacture (2600°F)
8. Incineration for waste disposal (up to 2600°F)
9. Cement manufacture (2500°F)
10. Gasification of coal (2500°F)
11. Wulff process for acetylene (1800°F - 2900°F)
12. By-product coke oven operation (1800°F - 2200°F)
13. Copper smelting in reverberatory furnace (2100°F)
14. Ore roasting, e.g. Spodumene decrepitation (2000°F)
15. Lime burning (below 2000°F)
16. Cracking of hydrocarbons (1800°F)
17. Reforming of natural gas (1500°F)
18. Retorting of oil shale (1350°F)
19. Cracking of ammonia (1200°F)
20. Production of HCN from methane and ammonia (?)

The above processes are discussed in detail in the NDA report in Chapter 4, Page 70.

FIG. 11
(FROM METALWORKING MAGAZINE)
(OCT. 15, 1959)

TABLE A REFRACTORY METALS

Ultimate tensile strength is on the upper line and 0.2% offset yield strength on the lower line.

METAL	MELTING POINT, F	DENSITY lb/cu in.	ELASTIC MODULUS (70 F), 10^6 psi	ULTIMATE TENSILE and 0.2% OFFSET YIELD STRENGTHS, 10^3 psi: 70 F	500 F	1000 F	1500 F	2000 F	2500 F	STRESS-TO-RUPTURE in 100 hr, 10^3 psi: 1500 F	2000 F	ELONGATION, % in 2": 70 F	1000 F	TEST SPECIMEN	WORKING TEMPERATURES	FABRICATION PROPERTIES	APPLICATIONS	AVAILABLE FORMS
TUNGSTEN	6152	0.70	51	250-100 ..	200-64 ..	170-48 nd-17	120-39 nd-15	75-34 nd-13	50-32 ..	nd-35	nd-22	nd-0	nd-59	Wrought mat'l; ranges = as-worked and annealed cond'ns.	Form as high above 750 F as possible; stress relieve 2000 F; recrystallizes 2300-2800 F.	Machine with carbide, 25-30 sfpm; preferably hot (1000 F); finish grind; extremely stiff; highly work hardenable.	Rocket nozzles; radiation shielding; x-ray targets; heating elements; counterweights; rapid oxidation above 1100 F.	Powder, wire, strip, rod, bar.
RHENIUM	5756	0.76	67	285-165 ..	255-143 ..	169-110 ..	140-94 ..	101-84 ..	80-50 ..	nd-28	nd-12	2-10	1-11	0.050" strip; ranges = as-worked (20% red'n) and annealed cond'ns.	Work at rm temp only; anneal 3100 F; recrystallizes about 2600 F.	Roll, swage and draw cold; work hardens rapidly; 10-20% max red'n between anneals.	Heavy-duty contacts; high temp thermocouples; Mo and W alloys; rapid oxidation above 1100 F.	Powder, rod, wire and strip; Chase Brass and Copper only supplier of wrought forms.
TANTALUM	5425	0.60	27	115-51 110-33	114-56 106-22	99-50 90-20	67-23 50-11	22-14 ..	..	nd-12	nd-5	19-40	10-25	7/16" bar; ranges = as-worked (87% red'n) and annealed cond'ns.	Work at rm temp only; stress relieve 1650 F; recryst. about 2100 F.	Very soft and ductile, tends to gall; when machined, use HSS, 100-300 sfpm; resistance weld, arc weld in pure helium.	Capacitors; corrosion-resistant process equipment; gettering.	Powder plus all mill forms, sheet (to 36").
MOLYBDENUM	4752	0.37	45	110-67 96-55	92-50 79-37	80-42 62-26	59-38 42-23	35-33 21-19	17 (recryst.) 10	40-18	14-11	15-37	12-45	Sheet mat'l; ranges = stress relieved and recryst cond'ns.	Form unalloyed Mo 0.020" - 0.100" sheet at 200-1000 F, Ti-alloys 400 deg higher; stress-relieve below recryst. temp which varies with amt of working, impurities etc; max recryst temps; unalloyed, 2150 F; Mo-½ Ti, 2450 F; Mo-Ti-Zr, 2700 F.	Highly abrasive; machine with carbides at 25-200 sfpm; rigid mach nec; easily brazable; res. weld or inert-gas arc weld in completely oxygen-free atmos; alloys are stiffer.	Electron tubes, furnace elements; rocket nozzles; future turbine buckets and other agt parts and high-temp skin material, start to oxide about 300 F, castastrophic above 1100 F unless coated.	Sheet (to 36"), foil, wire, rod, bar.
Mo-0.5% Ti	4730	0.37	46	122 105	110 95	105 85	88 77	55 49	24 (recryst.) nd	85-45	38-21	6	7	Sheet; stress-to-rupture data for stress-relieved and recryst cond'ns; all other values for stress-relieved mat'l only.				Same as unalloyed mat'l.
Mo-0.5Ti-0.08Zr	4725	0.37	47	123-79 100-55	.. ..	.. ..	98-55 nd-28	75-37 ..	48-19 ..	110-58	52-30	27-40	24-53	⅝" rolled rod; ranges = stress relieved and recrystallized cond'ns.				Not yet commercial.
COLUMBIUM	4380	0.31	16	61-33 51-23	57-28 51-nd	47-30 38-nd	21-13 17-nd	6-5 ..	..	20	5	22-60	17-30	Rod; ranges = as-worked and annealed cond'ns.	Work at rm temp only; unalloyed mat'l recrystallizes above 1400 F, tungsten alloy above 2800 F.	Unalloyed columbium is fabricated and welded like tantalum; alloys are stiffer, but some can be worked at rm temp.	Reactor fuel rod cladding for unalloyed metal; alloys being developed for high-stress, high-temperature applications in AGT, and structural parts and skins in aircraft and missiles; unalloyed metal starts to oxidize rapidly above 800 F; alloys have better strength and oxidation resistance, but still require protective coatings.	Sheet, strip, rod, bar.
Cb-15W-5Mo-1Zr	4500 (est)	0.34	25	125 85	110 78	95 70	82 60	65 44	..	..	35	22	18	Swaged bar (GE's F-48), as-worked; (rupture properties on annealed bar).				Not yet commercial.
Cb-33Ta-0.07 Zr	4550	0.38	..	80 70	..	..	..	45 40	..	..	17	23, (3% as-rolled)	16	Sheet (Fansteel 82); annealed data only.				Sheet (to 36"), strip, bar, rod.
Cb-10Mo-10Ti	4100	0.29	17	100 92	78 67	70 52	64 49	35 33	12 ..	..	9	22	19	Extruded-bar data only (DuPont alloy).				Sheet (to 6"), bar; semi-commercial status.

TABLE B LIGHT and REACTOR STRUCTURAL METALS

METAL	MELTING POINT, F	DENSITY lb/cu in.	ELASTIC MODULUS (70 F), 10^6 psi	ULTIMATE TENSILE and 0.2% OFFSET YIELD STRENGTHS, 10^3 psi: 70 F	600 F	1000 F	1200 F	ELONG., % in 2": 70 F	600 F	TEST SPECIMEN	WORKING TEMPERATURES	FABRICATION PROPERTIES	APPLICATIONS	AVAILABLE FORMS
ZIRCALOY-2	3325 (est)	0.24	14	95-65 90-38	nd-32 nd-20	 ..	 ..	3-25	nd-40	0.035" strip; ranges = as-rolled (35% red'n) and annealed; r.t. tens. strength is 50% higher in transverse than longit. directions.	Hot roll 1450-1650 F and anneal 1550 F in air (anneal c.w. mat'l in vac 1400 F); draw above 650 F.	Tends to gall; machine with carbide, heavy cut at 150-200 sfpm; drill and grind very slowly; res. weld or arc weld (Zr filler) in inert atmos; braze in vac; can be forged, rolled and drawn much like Ti; protect reactor grade from contam. by cladding.	Reactor fuel rod cladding and structural parts; corr-res. chem. process equipment commonly-used form of Zr, much better corrosion resistance.	Strip, sheet, plate, foil, tubing, wire, bars, rounds.
TITANIUM	3074	0.16	16	97 84	43 27	24 17	 ..	25	28	All data avg. for sheet mat'l in annealed cond'n only.	Form at 400-600 F to relieve spring-back; or cold form with intermediate stress relief at 800-1000 F.	Tends to gall and weld; machine at low speeds (20-75 sfpm) high feed rates, continuous cut and ample coolant; tends to spring back in forming; readily welded, requires inert atmos to prevent embrittlement; not hardenable by heat treatments.	Cooler parts of jet engines, such as compressor parts, air inlets, etc. operating at 350 F; corrosion resistant process equipment.	Sheet, strip, plate, bar, billet, tubing and wire.
Ti-5Al-2.5Sn (All-Alpha Alloy)	..	0.16	..	135 123	90 70	78 58	38 25	15	18	All data avg. for sheet mat'l in annealed cond'n only.	Form at 500-1000 F; deep draw 1000-1400 F; stress relieve 900-1200 F, anneal 1350-1500 F.	Machine as above; more diff. to form because of higher ys.; good weldability.	Compressor outer and intermediate cases, operating to 650 F; usable at higher temp than unalloyed Ti.	Sheet, strip, plate, bar, billet, tubing and wire.
Ti-2Cr-2Fe-2Mo (Alpha-Beta Alloy)	..	0.17	..	190-138 180-128	140-95 120-70	58-38 52-37	..	12-20	18-21	Sheet mat'l; ranges = aged and annealed cond'ns.	Easier forming 400-600 F; stress relieve 1050-1300 F; age 900-1000 F.	Machine as above; beta phase improves formability; welds strong, but brittle; generally not welded.	Various structural and skin components in aircraft.	Sheet, strip, bar, billet, tubing.
Ti-13V-11Cr-3Al (All-Beta Alloy)	..	0.17	14	195-140 175-135	160-115 135-103	145-100 120-93	.. ..	6-18	10-24	Sheet mat'l; ranges = aged and annealed cond'ns.	Many operations at r.t., esp. bending; various heat treatments above 700 F give desired physicals.	Very ductile; easier forming than most Ti alloys; can be cold headed; excellent weldability, esp. by TIG process; machine like other Ti alloys.	Solid propellant casings, structural air-frame parts, skins (B-70, F-108)	Sheet, some strip, foil, bar and billet.
BERYLLIUM	2345	0.07	44	80 65	58 48	35 32	 ..	12	25	Sheet mat'l; hot- and cross-rolled, annealed.	Form at 850-1400 F, depending on shape and thickness; stress relieve in same range; recryst. temp. 1400 F.	Machines like cast iron; use carbides, 150-250 sfpm, feeds to 0.015 ipr; simple forming and bending; join by brazing and soldering; welds rather brittle; dust toxic' see AEC health standards'	Fuel-rod cladding and neutron reflector; gyro parts; future aircraft and missile structure mat'l; heat-sink uses.	Pressed block, rod, tubing, foil, sheet, powder.

NOTE: Mechanical properties of many of these metals are greatly influenced by heat treatment, amount and type of working and impurities level. The values in these tables are representative for the test samples and conditions noted and give useful information on strength trends with temperature. However the strength of fabricated parts could vary from these values by 25-50%.

n d = no data

TABLE C SOME* SUPER ALLOYS AND ULTRA-STRENGTH STEEL

	ALLOY	ULTIMATE TENSILE and 0.2% OFFSET YIELD STRENGTHS, 10^3 psi: 70 F	500 F	800 F	1000 F	1400 F	1700 F	STRESS-TO-RUPTURE 100-Hr. 10^3 psi: 800 F	1000 F	1500 F	ELONG., % in 2": 70 F	1000 F	FABRICATION PROPERTIES
Superalloys	RENE 41 (Ni-base) 0.062" Sheet, S. T. 1950 F, Aged 1400 F	185 148	.. ..	.. ..	174 136	140 121	54 50	..	..	33	18	17	Machine fully hard, tung. carbide 30-60 sfpm, abt 1/16" cut, light feeds; inert-gas arc-weld; forge above 1850 F.
	M-252 (Ni-base) S. T. 1950 F, Aged 1400 F	175 98	.. ..	.. ..	144 94	115 87	50 53	..	..	37	25	31	Machine partially or fully annealed, low speeds, steady cut; form at elev. temp; inert-gas arc-weld in annealed cond'n.
	UDIMET-500 (Ni-base) sheet S. T. 2150 F, Aged 1400 F	235 200	.. ..	.. ..	230 193	135 105	58 50	..	..	53	10	14	Machine with HSS or carbides, 10-60 sfpm, cut 3/32-¼" abt 0.015" feed; inert-gas arc-weld or res. weld.
	INCONEL 713C (Ni-base) VM, VC, AC	122 108	.. ..	.. ..	119 103	130 105	90 68	..	..	58	8	8	Casting alloy.
	HAYNES 31 (Co-base) Bar, Aged 1350 F	128 113	.. ..	.. ..	92 70	70 50	33 ..	..	..	29	3	4	Casting alloy.
	J-1570 (Co-base) 0.062" Sheet, S. T. 2100 F, Aged 1650 F	138 77	.. ..	.. ..	127 74	100 68	35 28	..	..	36	15	14	Machine like Rene 41; more easily formed than nickel-base alloys, work hardens more slowly; arc- and resistance weld well.
	A-286 (Fe-base) S. T. 1800 F, Aged 1325 F	144 94	.. ..	.. ..	132 91	64 54	.. ..	..	99	14	24	19	Machine like austenitic SS in hard cond'n; can be cold-formed and drawn annealed; weld by usual processes in S. T. cond'n; cracking may be problem in large sections; anneal 1600-1800 F; age 1300-1400 F.
5% Cr Tool Steels	UNIMACH 1 0.075" Sheet Tempered 1075 F	243 207	233 194	215 180	180 145	.. ..	.. ..	195	95	..	8	17	Machinable and formable annealed; air hardening to 305,000 psi; weld by inert-gas arc; anneal 1500 F, temper 900-1000 F.
	UNIMACH 2 0.075" Sheet, Tempered 1075 F	255 215	235 195	215 179	181 145	.. ..	.. ..	160	70	..	5	10	Work like Unimach 1; somewhat higher room-temp. strength, less ductile than Unimach 1; air hardening to 317,000 psi.
	VASCOJET 1000 Tempered 1060 F	262 215	232 195	219 187	180 140	.. ..	.. ..	205 (after 100 hrs at temp)	80	..	10	11	Machine in annealed cond'n; can be formed cold or hot; good weldability by inert-gas arc; air hardening to 310,000 psi; anneal 1500 F, temper 950-1200 F.
Low-Alloy Steels	AIRSTEEL X-200 0.050" Sheet Tempered 900 F	250 200	230 175	195 160	125 110	.. ..	.. ..	140 (0.100" sheet)	..	..	10	10+	Machine like 4340, can be drawn and spun in annealed cond'n.; inert-gas arc weld; air hardening to 310,000 psi; tempering range 600-750 F.
	17-22AS Tempered 1225 F	150 127	140 116	121 101	91 78	.. ..	.. ..	140	40	..	17	18	Readily machined and formed in annealed cond'n.; low work hardening; weldable by all processes; air hardening; stress relieve 1250 F, full anneal 1450 F, usual temper 1100-1300 F.
	300 M Tempered 600 F	285 240	270 200	(700F) 230 175	..	..	..	..	..	..	10	(700F) 15	Machine annealed; heat 100 deg above hot forming temps usual for steel; weldable by all methods; anneal 1275; temper 500-600 F; air hardening to 300,000 psi.

* Partial listing. Other alloys for these applications include:

(1) Nickel-base superalloys: Udimet 500, Udimet 700, Waspaloy, Inconel 700, Incoloy 901, GMR 235, GMR 235D, Hastelloy R-235, Hastelloy X, Nicrotung, Nimonic 80A, Nimonic 90, Refractaloy 26, DCM, Unitemp 500.
(2) Cobalt-base superalloys: X-40, S-816, J-1650, Haynes 25, Haynes 21, Multimet, L-605.
(3) Iron-base superalloys: M-308, Discaloy, Unitemp 212, W-545, N-155.
(4) 5% chromium tool steels: Potomac M, Potomac A, Halmo, Thermold J, Peerless 56 (3% Cr), H11.
(5) Low-alloy ultra-strength steels: AISI 4340, 4330, 4360, Hy-Tuf, UHS-260, USS Strux, HS 220, HS 260, Tricent, Super Tricent, 5-317.

NOTE: Strengths above are typical for heat treatments noted. Treatments can be tailored to give desired strength and hardness for specific service conditions. Room Temp. elastic modulus for most superalloys and steels is 30-35 million psi, and density about 0.3 lb/cu ft.

Price $1.25 . *Available from the Office of Technical Services, Department of Commerce, Washington 25, D.C.*