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Los Alamos Nuclear Rocket Project Rover*

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The objective of Project Rover is to demonstrate the feasibility of nuclear rocket propulsion. The simplest type of nuclear rocket engine is basically a solid to gas heat exchanger in which the heat is generated by fission. This is not a new idea but active work leading to the present program began at Los Alamos in 1954. A study group was formed as a result of interest among individuals at Los Alamos with the result that a feasibility report was prepared in early 1955. Following this, the Atomic Energy Commission decided formally to establish a program for demonstration of the feasibility of nuclear rocket propulsion at the Los Alamos Scientific Laboratory and at the University of California Radiation Laboratory at Livermore. In 1956 a review of the work took place which resulted in early 1957 in re-direction of the Livermore Laboratory to the nuclear powered ramjet, Project Pluto. It was in early 1957 that work at Los Alamos crystallized into a specific item, i. e., a uranium loaded graphite fueled reactor named Kiwi-A which was tested on July 1, 1959.

* Work performed under the auspices of the United States Atomic Energy Commission

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During this period, development of the reactor itself was the pacing item for the program but in addition to the Laboratory's work on the reactor and an appropriate test facility at the Nevada Test Site there was concurrent work supported by Air Force funding on supporting items. This was notably (1) over-all engine and vehicle studies, and (2) development of nozzles, pumps, etc. This work was largely carried out by Aerojet General and Rocketdyne Division of North American Aviation. In the summer of 1958, cognizance of the Rover Program was transferred from the Air Force to the newly formed NASA. The dual administration of AEC-AF and AEC-NASA was resolved in the summer of 1960 by agreement of the Atomic Energy Commission and NASA forming the Space Nuclear Propulsion Office (SNPO) which now sponsors and coordinates Rover under the direction of Mr. Harold B. Finger.

Since the program was established, the Los Alamos Laboratory has carried out hot nuclear test of six reactors^{*} with results sufficiently encouraging that in 1960 and early 1961 a paper study was made of reactor in-flight testing (RIFT). This has been followed with establishment of the NERVA (Nuclear Engine for Rocket Vehicle Application) project in 1961. The NERVA project has as its objective the construction and test of a flyable reactor of the type developed by Los Alamos in Project Rover. The NERVA project has been assigned to Aerojet General as prime contractor with Westinghouse as a subcontractor to Aerojet for the construction of the reactor. This will be followed by the Reactor In-Flight Test (RIFT) phase of the development.

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Considerations in Reactor Design

Thrust is obtained from the nuclear rocket engine by expelling matter at high velocity through a nozzle much the same as in a chemical rocket. The first generation of nuclear rocket engines is based on a solid-to-gas heat exchanger in which the nuclear reactor is a porous solid through which the propellant is passed. The specific impulse of the propellant system is roughly proportional to the square root of absolute temperature of the propellant and inversely proportional to the square root of the mean molecular weight of the propellant. The attractiveness of the heat exchanger nuclear rocket derives in large part from the opportunity to substitute hydrogen for the higher molecular weight gases which result from combustion in chemical rockets. It is unfortunate that liquid hydrogen has such a low density and that its boiling point is so low. As a result, tanks are of large volume and there are problems of two-phase flow in the handling of the liquid and its vaporization. Likewise, gaseous hydrogen at high temperature is not a chemically inert material. In view of the importance of propellant temperature, the reactor core must of course be constructed of the most refractory materials available.

The design of a nuclear rocket test reactor is a process involving the fusion of contributions from several major fields which may be described as (a) materials, (b) neutronics, (c) heat transfer and fluid flow, (d) structural design, and (e) reactor control. This would not be so difficult

if evolution of a design were permitted to be slow and orderly but nowadays it seems to be necessary to telescope the time scale of big projects to the utmost. This requires the closest cooperation and a lot of give and take between contributing groups so that concurrent development may proceed on the several aspects of the problem on the basis of the current best judgment of all parties.

A paramount consideration in design of a nuclear rocket expected to produce a thrust level of more than 1 g is that the power density must be of the order of 100 megawatts per cubic foot. This by far transcends any other type of reactor in existence and the requirement for removal of this enormous amount of heat imposes severe restrictions on heat transfer and fluid flow design of the reactor. A critical assembly must be achieved with the requisite detailed neutron economy and detailed flux distribution. Experimental results with a neutronic mock-up of the calculated reactor makes possible the final design of the actual test reactor. The reactor must be controllable over an unprecedented temperature range and must change ⁹ power by orders of magnitude in tens of seconds. Fuel elements capable of meeting the neutronic requirements, the heat transfer and fluid flow conditions, as well as having the mechanical properties to make a sound reactor structure and capable of withstanding the highest possible temperature in operation, have to be developed and manufactured.

Component tests, simulating the conditions to be encountered in the rocket engine, offer a means of testing substantially all except the effect

of vibration and radiation. Tests which would reproduce these factors of environment may be so expensive of time, manpower and money as to be substantially impractical. The real vibration environment of the rocket engine is not known at the present time and the radiation level of rocket reactors exceeds that in such reactors as MTR and ETR by a large amount. The effects of reactor radiation on materials or components can be simulated to a degree by accumulating irradiation to the desired total using some available reactor and testing the material or part after such irradiation. In many instances, however, the temperature of the material in actual use would be high enough to result in annealing out a significant fraction of the radiation damage. The study of radiation effects on core materials as well as structural and auxiliary equipment is therefore best done by experiments carried out in actual reactor tests and by examination of reactor parts after full power tests.

A component test which has been of the greater usefulness to the materials program is the testing of fuel elements in a resistance heated electric furnace. Here the current passes directly through the fuel element so that heat is generated within the fuel element as it would be in a reactor. It is necessary to have heat generation very close to the coolant-solid interface because at these power densities even a good thermal conductor like graphite would produce a temperature gradient of hundreds of degrees in a fraction of an inch. Consideration of the power density will show that the electric power demand would be too big for a realistic test of more than

a very small fraction of a reactor. Nevertheless, tests of electrically heated single fuel elements are our most important source of information about the life of fuel elements as a function of temperature, time, gas flow, and pressure, etc.

After the actual reactor is assembled, its range of reactivity is measured and the fission distribution in the core determined to establish the uniformity of power generation in the core. "Cold flow" tests of the complete reactor in which propellant passes through the core provide an integral test of the interaction of systems without the complications of high temperature and fission in the reactor, and of course the reactor can be worked on after the exercise is finished. Finally, the "hot" test of the complete reactor system under actual operating conditions furnishes the final trial of components and integral structure and the interactions of the several systems involved.

Materials Problems

It would be an understatement to say that the life of the materials man trying to satisfy the desires of the neutronic designer and the propulsion engineer is complicated. First of all, the rocket reactor must obviously contain sufficiently fissionable material and have small enough neutron absorption so that it constitutes a critical assembly. The propulsion engineer would of course like to have the core operate within a few degrees of the melting point of the most refractory materials in order to maximize specific impulse. The materials man is expected to find a refractory material

somehow containing uranium, having near zero neutron absorption cross section and a melting point like 3000°C . The propulsion engineer would like to turn the reactor on and off like a light bulb but this is hardly customary with nuclear reactors and creates severe problems of thermal stress and reactor control. From a neutronic viewpoint, a propellant which affects neutronic behavior is undesirable, but the propulsion engineer must have the highest available specific impulse and for this supremely important reason insists on hydrogen as a propellant. If it is corrosive to many materials at high temperature or affects the neutron economy of the reactor, then the materials man and neutronic designer have a problem to solve. It is pretty obvious that the conflicting desires of even these three parties to the design alone are not easy to reconcile but compromises must be found in order to reach a successful design.

Prior to the start of the Rover Program there was not a large backlog of basic information to serve as a foundation for specific hardware development. In particular, the physical and chemical properties of the highly refractory materials suitable for fuel element construction were little known. As seems to be the practice nowadays, it was decided to try to carry on an investigation of properties of materials and obtain other essential basic information concurrently with the specific development program for the design, fabrication, and operation of the end device, in this case experimental rocket reactors. The members of the first series of experimental test devices have been called "Kiwi" reactors.

Since the fuel element consists, as it must, of more than fissionable material alone, the nuclear properties of the added material will inescapably affect the neutronics of the reactor. All of the atoms within the core of the reactor compete for neutrons. It is customary to distinguish the thermal neutron absorption cross section and the resonance absorption integral which is a measure of the absorption of epithermal and higher energy neutrons. The neutron absorption of the materials which are sufficiently refractory to be useful for fuel elements varies widely with the result that a reactor concept which is feasible with one material may be useless with another. To take one extreme, the thermal neutron absorption cross section of carbon is very small, 0.0045 barns, and the resonance absorption integral zero barns. Such a material, which is also a good moderator, can readily be used in a homogeneous reactor design. Such is not the case with, for example, tungsten, whose thermal neutron absorption cross section is 19 barns and resonance absorption integral about 450 barns. These quantities are so large that the use of tungsten in a homogeneous reactor appears impractical and the designer is therefore forced to an inhomogeneous structure in which neutrons can be moderated in regions which do not contain large amounts of tungsten. Thus the realization of an epithermal reactor using tungsten appears difficult while with graphite it does not appear difficult. For a price, the problems of design with tungsten could be greatly alleviated by using tungsten 184 which constitutes almost one-third of natural tungsten and whose thermal absorption cross section is about 2 barns. Tantalum has about the same neutron absorption characteristics as tungsten, while niobium

and molybdenum have much smaller absorption cross sections and zirconium cross sections are two orders of magnitude smaller.

The highly refractory substances may be divided into three classes: (a) metals; (b) refractory "ceramic" compounds; and (c) graphite.

The very refractory metals include tantalum, molybdenum, tungsten, rhenium, osmium, ruthenium, and a few others. The platinum family metals are not merely expensive and scarce but hard to fabricate. Rhenium is likewise not plentiful. Tantalum absorbs hydrogen in the temperature range 350 to 650°C, becoming brittle as a result, and since the reactor must pass through the temperature range of embrittlement when heating to operating temperature and cooling down, this would be a very difficult characteristic to accommodate in design of a fuel element. Consequently, for practical purposes, the refractory metals are tungsten and molybdenum.

A great deal more study of the physical properties of refractory metals is needed. However, substantial contributions to knowledge of the creep properties of tungsten and molybdenum have been made recently. The creep-rupture behavior of commercial powder-metallurgy tungsten rod was studied in the temperature range 2250 to 2800°C (Ref. 1).

Ref. 1 Short Time Creep-Rupture Behavior of Tungsten, 2250°C to 2800°C, W. V. Green, Trans. Met. Soc. of AIME, 215, December 1959, p. 1057.

The logarithm of stress versus logarithm of rupture time was found to be linear. It was also found that the logarithm of rupture time is a linear

function of the logarithm of the initial stress. The investigator went on to study the Zener-Holloman temperature compensated creep rate parameter and also found that the Larson-Miller parameter, Z , is a linear function of the logarithm of initial stress. A similar study was made of molybdenum. Tungsten and molybdenum recrystallize at a disappointingly low fraction of their melting point which complicates the problem of devising a structure that will use them. For example, a 1 mil foil of molybdenum whose structure initially is fibrous and tough, recrystallizes completely in 20 minutes at 1800°C and becomes a brittle substance lacking in strength. The onset of recrystallization can be somewhat delayed both in rate and temperature by "doping" with a variety of substances as was learned years ago in the manufacture of tungsten lamp filaments. A "doped" molybdenum foil, which was also heat treated for 20 minutes at 1800°C retains its original fibrous structure almost unchanged but if the treatment temperature is raised to 2000°C , grain growth restraint fails. Thus the maximum working temperature for molybdenum might be taken to be 1800°C , less than 70% of the melting point which is 2650°C .

The refractory "ceramics" of interest are compounds of transition metals of groups four, five and six of the periodic table. Unlike the compounds studied in elementary chemistry, these compounds do not have fixed molecular formulae but composition commonly is variable over a range. Thus a knowledge of the phase diagram of the system is necessary to an understanding of the material. Many of these substances do not evaporate congruently, i. e., the material lost by evaporation does not have the same composition as the remaining material. It follows that the

composition and properties of the residue change continuously. Furthermore, different compounds are subject to this effect to varying degrees. At one extreme, for example, is TaC which loses carbon preferentially by evaporation and indeed if time and temperature are great enough apparently tends toward complete loss of carbon. Of course, even moderate change in composition can result in very substantial changes in properties. At the opposite extreme is ZrC which evaporates congruently. In general, the compounds of this type have not been extensively studied, and their mechanical properties are not well known. As a class, although they are hard and strong at moderate temperatures, they are generally brittle, which makes them difficult to fabricate or use. Their thermal stress resistance, based on room temperature properties, is substantially less than that of graphite or the refractory metals.

Graphite is in a class by itself and, while it is neither strong nor ductile by comparison with metals at room temperature, it retains its strength to temperatures upwards of 2500°C where its strength is of the same order as tungsten. Graphite is generally thought of as a brittle substance, but at high temperatures it becomes progressively more plastic but remains solid to its sublimation point which at atmospheric pressure is about 3925°C . It exhibits creep as shown in Figure 1 for a uranium loaded graphite (Ref. 2).

Ref. 2 High Temperature Properties of Graphite, II. Creep in Tension.

P. Wagner, A. R. Driesner, L. A. Haskins. J. Appl. Phys., 30, No. 2., p. 52.

It can be made into desired shapes with not too great difficulty.

Graphite has good thermal conductivity and is well known to be resistant to thermal stress. In addition, its neutron absorption is trivial. Altogether, it was decided that the Kiwi reactors would be made using graphite based fuel elements made at LASL and structural parts made from commercial graphites.

Reactor Construction and Test

In order to minimize fuel volume, the first reactor experiment, called Kiwi-A, consisted of a thick-walled cylinder of fuel surrounding a central island of D_2O and the core was surrounded by a thick graphite reflector (Figure 2). Gaseous hydrogen from the main coolant inlet manifold went into the inlet plenum and then entered the reflector where it flowed down to a plenum at the cool end of the core, then up through the core and out the nozzle. A water cooled double-walled nozzle made by Rocketdyne was used. The reactor was contained in a water cooled double-walled aluminum pressure vessel. The fuel consisted of uranium-loaded graphite plates each 8" long x 1/4" thick and varying in width from 5" to 8". Ribs about 50 mils high were machined on the surface of each plate so that when the plates were stacked they were separated by gas passages. The fuel plates were made at LASL by adding UO_2 to the graphite "green mix." The amount of uranium added was uniform in a given plate and the amount in a given plate differed depending on the axial or radial position of the plate and on heat transfer and fission distribution calculations. The stacked plates were held in four cylindrical boxes, called "whims," made of graphite (Figure 3).

A fifth "whim," nearest the upper (exit) end of the core, contained unloaded graphite plates. ACF Industries was responsible to LASL for detailed design and fabrication of a large part of the non-nuclear hardware, as well as for later field assembly at the Nevada Test Site and for disassembly. The initial reactor assembly was carried out at the Albuquerque Division of ACFI. This was followed by a low power check of operation at Los Alamos, followed by assembly at the reactor test site in Nevada.

A facility for Rover tests, called the Nuclear Rocket Development Site (NRDS), has been built up in a region to the west of the bomb test area at the Nevada Test Site. In view of the intense radiation from the rocket reactor, the control room was located almost two miles from the test cell. The reactor was assembled before test and later disassembled after test in a facility called the MAD Building which was also about two miles from the test cell and an equal distance from the control room. The reactor was assembled on a test cart which was essentially a flat car and was transported to the test cell over a railroad track where it was plugged into the test cell in a fashion which would permit easy remote disconnection after test for return to the MAD Building for disassembly.

At present, in addition to the original test cell (A), a second and larger facility, Test Cell C, has been built. Each test cell complex has a tank farm for storage of gaseous hydrogen, nitrogen and helium and a two liquid hydrogen dewars which can be pressurized to 100 psi. The test cell buildings contain the gas and liquid handling equipment, which includes valves, hydraulic systems and a turbopump for the liquid hydrogen. This

part of the building is filled with nitrogen when hydrogen is flowing in order to prevent the possibility of hydrogen explosion in the event of a leak. In another part of the test cell is located the electronic equipment for transmission of both control signals and instrumentation data giving information about reactor performance.

The design of nuclear rocket reactors involves problems of reactor control which differ from conventional power reactors. The high power density and large range of operating temperature, together with the requirement of rapid turn-on and shut-down, demand rapid changes of many orders of magnitude in reactivity with the result that the control system must include a fairly complex analog computer. The central island of Kiwi-A (Figure 1) contained vertical acting control rods containing cadmium for regulating, shimming and scrambling the reactor. These were operated by linear hydraulic double acting pistons operating through seals. The intense radiation necessitates attention to radiation damage problems. Bendix Research Division and General Electric Aircraft Accessory Turbine Department have worked on development of radiation resistant control activators for the Atomic Energy Commission. The first reactor was more or less manually controlled. In a later reactor, Kiwi-B, a larger degree of automation was employed. A computer receives information on temperature of exit gas, power level and flow rate of gas. The programmed power demand is fed in effectively by a potentiometer setting which is compared with the actual power level from neutron detectors and the resultant power error controls the control rod motion.

The flow rate demanded, $\dot{W}_D$, is generated by a programmed potentiometer setting. The actual flow rate, $\dot{W}_A$, is sensed from the pressure drop through the system and inlet venturi temperature. From this the analog computer determined the error, $\dot{W}_E$, which drives a throttling valve. The neutron level is determined by ion chambers, and several logarithmic and linear channels are reported to the control room. Period and power scrams guard against excessive excursions. The transmission, calibration of instruments and recording of data was the responsibility of Edgerton, Germeshausen and Grier Corporation. A large number of thermocouples, pressure taps and position transducers were used so that altogether hundreds of transmission lines from test cell to control room are required for a test.

Examination of a reactor after test is a source of a large part of the materials information that is obtained. After completion of test, remotely operated devices separate the reactor and test car from the test cell. Following return of the reactor to the shielded portion of the MAD Building, disassembly is accomplished with remote manipulators. Power generation from point to point in the reactor is measured by gamma counting the fuel elements and by radiochemistry of samples taken from them. Temperature from point to point can be obtained during the reactor run up to the capabilities of available thermocouples, but in the hotter part of the core the thermocouples are destroyed when the temperature gets up to the operating point. A technique for determining the maximum temperature attained during the reactor run from point to point has been developed employing

tiny bits of refractory metals enclosed in the graphite capsules. The temperature at which each type of metal changes appearance appreciably is determined by calibration experiments in the Laboratory so that a rather coarsely calibrated thermometer is available telling that the temperature at a point lay between the indicating points of a pair of metals separated by a temperature like 100°C .

The second reactor experiment, Kiwi-A¹, took place in July 1960. The external features of the reactor were deliberately made like Kiwi-A in the interest of simplifying the engineering task of the Laboratory. This reactor employed the programmer for the power increase to slave gas flow to power demand so that the rate of change of temperature with time could be controlled. A third reactor experiment, Kiwi-A3, was carried out in October 1960. These tests in 1960 provided several experiments on reactor response to random commands fed in by punched tape. The first test of the Kiwi-B series also employed gaseous hydrogen and provided a check on design changes and detailed operating characteristics of the reactor for later tests.

In mid-1960 work was started on a new test cell of larger capacity intended for a liquid hydrogen test of reactors. The original test cell was also equipped for liquid hydrogen.* The reactivity increment produced by introduction of gaseous hydrogen through a reactor is not very disturbing to the neutronic behavior of the reactor. However, the ΔK from the denser liquid hydrogen particularly during start-up is a very different matter.

* Tests of reactors using liquid hydrogen were carried out in September and November 1962.

Heat transfer and flow stability are difficult to predict since there is necessarily a liquid to vapor transition zone. The low density and specific heat of liquid hydrogen give rise to problems of two-phase flow which require investigation. In a sense, the problem of introducing liquid hydrogen into a rocket reactor resembles pouring water into a tube boiler at red heat. The major objectives of the Kiwi-B series of reactor experiments include study of the start-up and full power operation of reactors on liquid hydrogen and selection of a basic design of a reactor to carry forward into the NERVA (Nuclear Engines for Rocket Vehicle Application) phase of the program which is to follow. The prime contract for this work is assigned to Aerojet General with Westinghouse Astronuclear Laboratory working on the reactor as a subcontractor.

To get from where we are now through the NERVA program to the RIFT (Reactor In Flight Test) will require advance on all fronts, but the materials aspect of the work will no doubt, in the end, set the boundary to what can be accomplished.

KIWI-B CONTROL SCHEMATIC
AUTOMATIC PROGRAMMED OPERATION

Figure 4

Fig. 3 View of Fifth Whim Before Assembly.

Figure 2

Cutaway section of Kiwi-A

Figure 1

Experimental tension creep curves showing the effects of stress (reduced) and temperature on graphite containing 1/4 gram U/cc. Reduced stress means stress/breaking stress.

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somehow containing uranium, having near zero neutron absorption cross section and a melting point like 3000°C . The propulsion engineer would like to turn the reactor on and off like a light bulb but this is hardly customary with nuclear reactors and creates severe problems of thermal stress and reactor control. From a neutronic viewpoint, a propellant which affects neutronic behavior is undesirable, but the propulsion engineer must have the highest available specific impulse and for this supremely important reason insists on hydrogen as a propellant. If it is corrosive to many materials at high temperature or affects the neutron economy of the reactor, then the materials man and neutronic designer have a problem to solve. It is pretty obvious that the conflicting desires of even these three parties to the design alone are not easy to reconcile but compromises must be found in order to reach a successful design.

Prior to the start of the Rover Program there was not a large backlog of basic information to serve as a foundation for specific hardware development. In particular, the physical and chemical properties of the highly refractory materials suitable for fuel element construction were little known. As seems to be the practice nowadays, it was decided to try to carry on an investigation of properties of materials and obtain other essential basic information concurrently with the specific development program for the design, fabrication, and operation of the end device, in this case experimental rocket reactors. The members of the first series of experimental test devices have been called "Kiwi" reactors.

Since the fuel element consists, as it must, of more than fissionable material alone, the nuclear properties of the added material will inescapably affect the neutronics of the reactor. All of the atoms within the core of the reactor compete for neutrons. It is customary to distinguish the thermal neutron absorption cross section and the resonance absorption integral which is a measure of the absorption of epithermal and higher energy neutrons. The neutron absorption of the materials which are sufficiently refractory to be useful for fuel elements varies widely with the result that a reactor concept which is feasible with one material may be useless with another. To take one extreme, the thermal neutron absorption cross section of carbon is very small, 0.0045 barns, and the resonance absorption integral zero barns. Such a material, which is also a good moderator, can readily be used in a homogeneous reactor design. Such is not the case with, for example, tungsten, whose thermal neutron absorption cross section is 19 barns and resonance absorption integral about 450 barns. These quantities are so large that the use of tungsten in a homogeneous reactor appears impractical and the designer is therefore forced to an inhomogeneous structure in which neutrons can be moderated in regions which do not contain large amounts of tungsten. Thus the realization of an epithermal reactor using tungsten appears difficult while with graphite it does not appear difficult. For a price, the problems of design with tungsten could be greatly alleviated by using tungsten 184 which constitutes almost one-third of natural tungsten and whose thermal absorption cross section is about 2 barns. Tantalum has about the same neutron absorption characteristics as tungsten, while niobium

and molybdenum have much smaller absorption cross sections and zirconium cross sections are two orders of magnitude smaller.

The highly refractory substances may be divided into three classes: (a) metals; (b) refractory "ceramic" compounds; and (c) graphite.

The very refractory metals include tantalum, molybdenum, tungsten, rhenium, osmium, ruthenium, and a few others. The platinum family metals are not merely expensive and scarce but hard to fabricate. Rhenium is likewise not plentiful. Tantalum absorbs hydrogen in the temperature range 350 to 650°C, becoming brittle as a result, and since the reactor must pass through the temperature range of embrittlement when heating to operating temperature and cooling down, this would be a very difficult characteristic to accommodate in design of a fuel element. Consequently, for practical purposes, the refractory metals are tungsten and molybdenum.

A great deal more study of the physical properties of refractory metals is needed. However, substantial contributions to knowledge of the creep properties of tungsten and molybdenum have been made recently. The creep-rupture behavior of commercial powder-metallurgy tungsten rod was studied in the temperature range 2250 to 2800°C (Ref. 1).

Ref. 1 Short Time Creep-Rupture Behavior of Tungsten, 2250°C to 2800°C, W. V. Green, Trans. Met. Soc. of AIME, 215, December 1959, p. 1057.

The logarithm of stress versus logarithm of rupture time was found to be linear. It was also found that the logarithm of rupture time is a linear

function of the logarithm of the initial stress. The investigator went on to study the Zener-Holloman temperature compensated creep rate parameter and also found that the Larson-Miller parameter, Z , is a linear function of the logarithm of initial stress. A similar study was made of molybdenum. Tungsten and molybdenum recrystallize at a disappointingly low fraction of their melting point which complicates the problem of devising a structure that will use them. For example, a 4 mil foil of molybdenum whose structure initially is fibrous and tough, recrystallizes completely in 20 minutes at 1800°C and becomes a brittle substance lacking in strength. The onset of recrystallization can be somewhat delayed both in rate and temperature by "doping" with a variety of substances as was learned years ago in the manufacture of tungsten lamp filaments. A "doped" molybdenum foil, which was also heat treated for 20 minutes at 1800°C retains its original fibrous structure almost unchanged but if the treatment temperature is raised to 2000°C , grain growth restraint fails. Thus the maximum working temperature for molybdenum might be taken to be 1800°C , less than 70% of the melting point which is 2650°C .

The refractory "ceramics" of interest are compounds of transition metals of groups four, five and six of the periodic table. Unlike the compounds studied in elementary chemistry, these compounds do not have fixed molecular formulae but composition commonly is variable over a range. Thus a knowledge of the phase diagram of the system is necessary to an understanding of the material. Many of these substances do not evaporate congruently, i. e., the material lost by evaporation does not have the same composition as the remaining material. It follows that the

composition and properties of the residue change continuously. Furthermore, different compounds are subject to this effect to varying degrees. At one extreme, for example, is TaC which loses carbon preferentially by evaporation and indeed if time and temperature are great enough apparently tends toward complete loss of carbon. Of course, even moderate change in composition can result in very substantial changes in properties. At the opposite extreme is ZrC which evaporates congruently. In general, the compounds of this type have not been extensively studied, and their mechanical properties are not well known. As a class, although they are hard and strong at moderate temperatures, they are generally brittle, which makes them difficult to fabricate or use. Their thermal stress resistance, based on room temperature properties, is substantially less than that of graphite or the refractory metals.

Graphite is in a class by itself and, while it is neither strong nor ductile by comparison with metals at room temperature, it retains its strength to temperatures upwards of 2500°C where its strength is of the same order as tungsten. Graphite is generally thought of as a brittle substance, but at high temperatures it becomes progressively more plastic but remains solid to its sublimation point which at atmospheric pressure is about 3925°C . It exhibits creep as shown in Figure 1 for a uranium loaded graphite (Ref. 2).

Ref. 2. High Temperature Properties of Graphite, II. Creep in Tension.

P. Wagner, A. R. Driesner, L. A. Haskins. J. Appl. Phys., 30, No. 2., p. 52.

It can be made into desired shapes with not too great difficulty.

Graphite has good thermal conductivity and is well known to be resistant to thermal stress. In addition, its neutron absorption is trivial. Altogether, it was decided that the Kiwi reactors would be made using graphite based fuel elements made at LASL and structural parts made from commercial graphites.

Reactor Construction and Test

In order to minimize fuel volume, the first reactor experiment, called Kiwi-A, consisted of a thick-walled cylinder of fuel surrounding a central island of D_2O and the core was surrounded by a thick graphite reflector (Figure 2). Gaseous hydrogen from the main coolant inlet manifold went into the inlet plenum and then entered the reflector where it flowed down to a plenum at the cool end of the core, then up through the core and out the nozzle. A water cooled double-walled nozzle made by Rocketdyne was used. The reactor was contained in a water cooled double-walled aluminum pressure vessel. The fuel consisted of uranium-loaded graphite plates each 8" long x 1/4" thick and varying in width from 5" to 8". Ribs about 50 mils high were machined on the surface of each plate so that when the plates were stacked they were separated by gas passages. The fuel plates were made at LASL by adding UO_2 to the graphite "green mix." The amount of uranium added was uniform in a given plate and the amount in a given plate differed depending on the axial or radial position of the plate and on heat transfer and fission distribution calculations. The stacked plates were held in four cylindrical boxes, called "whims," made of graphite (Figure 3).

A fifth "whim," nearest the upper (exit) end of the core, contained unloaded graphite plates. ACF Industries was responsible to LASL for detailed design and fabrication of a large part of the non-nuclear hardware, as well as for later field assembly at the Nevada Test Site and for disassembly. The initial reactor assembly was carried out at the Albuquerque Division of ACFI. This was followed by a low power check of operation at Los Alamos, followed by assembly at the reactor test site in Nevada.

A facility for Rover tests, called the Nuclear Rocket Development Site (NRDS), has been built up in a region to the west of the bomb test area at the Nevada Test Site. In view of the intense radiation from the rocket reactor, the control room was located almost two miles from the test cell. The reactor was assembled before test and later disassembled after test in a facility called the MAD Building which was also about two miles from the test cell and an equal distance from the control room. The reactor was assembled on a test cart which was essentially a flat car and was transported to the test cell over a railroad track where it was plugged into the test cell in a fashion which would permit easy remote disconnection after test for return to the MAD Building for disassembly.

At present, in addition to the original test cell (A), a second and larger facility, Test Cell C, has been built. Each test cell complex has a tank farm for storage of gaseous hydrogen, nitrogen and helium and a two liquid hydrogen dewars which can be pressurized to 100 psi. The test cell buildings contain the gas and liquid handling equipment, which includes valves, hydraulic systems and a turbopump for the liquid hydrogen. This

part of the building is filled with nitrogen when hydrogen is flowing in order to prevent the possibility of hydrogen explosion in the event of a leak. In another part of the test cell is located the electronic equipment for transmission of both control signals and instrumentation data giving information about reactor performance.

The design of nuclear rocket reactors involves problems of reactor control which differ from conventional power reactors. The high power density and large range of operating temperature, together with the requirement of rapid turn-on and shut-down, demand rapid changes of many orders of magnitude in reactivity with the result that the control system must include a fairly complex analog computer. The central island of Kiwi-A (Figure 1) contained vertical acting control rods containing cadmium for regulating, shimming and scrambling the reactor. These were operated by linear hydraulic double acting pistons operating through seals. The intense radiation necessitates attention to radiation damage problems. Bendix Research Division and General Electric Aircraft Accessory Turbine Department have worked on development of radiation resistant control activators for the Atomic Energy Commission. The first reactor was more or less manually controlled. In a later reactor, Kiwi-B, a larger degree of automation was employed. A computer receives information on temperature of exit gas, power level and flow rate of gas. The programmed power demand is fed in effectively by a potentiometer setting which is compared with the actual power level from neutron detectors and the resultant power error controls the control rod motion.

The flow rate demanded, W_D , is generated by a programmed potentiometer setting. The actual flow rate, W_A , is sensed from the pressure drop through the system and inlet venturi temperature. From this the analog computer determined the error, W_E , which drives a throttling valve. The neutron level is determined by ion chambers, and several logarithmic and linear channels are reported to the control room. Period and power scrams guard against excessive excursions. The transmission, calibration of instruments and recording of data was the responsibility of Edgerton, Germeshausen and Grier Corporation. A large number of thermocouples, pressure taps and position transducers were used so that altogether hundreds of transmission lines from test cell to control room are required for a test.

Examination of a reactor after test is a source of a large part of the materials information that is obtained. After completion of test, remotely operated devices separate the reactor and test car from the test cell. Following return of the reactor to the shielded portion of the MAD Building, disassembly is accomplished with remote manipulators. Power generation from point to point in the reactor is measured by gamma counting the fuel elements and by radiochemistry of samples taken from them. Temperature from point to point can be obtained during the reactor run up to the capabilities of available thermocouples, but in the hotter part of the core the thermocouples are destroyed when the temperature gets up to the operating point. A technique for determining the maximum temperature attained during the reactor run from point to point has been developed employing

tiny bits of refractory metals enclosed in the graphite capsules. The temperature at which each type of metal changes appearance appreciably is determined by calibration experiments in the Laboratory so that a rather coarsely calibrated thermometer is available telling that the temperature at a point lay between the indicating points of a pair of metals separated by a temperature like 100°C .

The second reactor experiment, Kiwi-A', took place in July 1960. The external features of the reactor were deliberately made like Kiwi-A in the interest of simplifying the engineering task of the Laboratory. This reactor employed the programmer for the power increase to slave gas flow to power demand so that the rate of change of temperature with time could be controlled. A third reactor experiment, Kiwi-A3, was carried out in October 1960. These tests in 1960 provided several experiments on reactor response to random commands fed in by punched tape. The first test of the Kiwi-B series also employed gaseous hydrogen and provided a check on design changes and detailed operating characteristics of the reactor for later tests.

In mid-1960 work was started on a new test cell of larger capacity intended for a liquid hydrogen test of reactors. The original test cell was also equipped for liquid hydrogen.* The reactivity increment produced by introduction of gaseous hydrogen through a reactor is not very disturbing to the neutronic behavior of the reactor. However, the ΔK from the denser liquid hydrogen particularly during start-up is a very different matter.

* Tests of reactors using liquid hydrogen were carried out in September and November 1962.

Heat transfer and flow stability are difficult to predict since there is necessarily a liquid to vapor transition zone. The low density and specific heat of liquid hydrogen give rise to problems of two-phase flow which require investigation. In a sense, the problem of introducing liquid hydrogen into a rocket reactor resembles pouring water into a tube boiler at red heat. The major objectives of the Kiwi-B series of reactor experiments include study of the start-up and full power operation of reactors on liquid hydrogen and selection of a basic design of a reactor to carry forward into the NERVA (Nuclear Engines for Rocket Vehicle Application) phase of the program which is to follow. The prime contract for this work is assigned to Aerojet General with Westinghouse Astronuclear Laboratory working on the reactor as a subcontractor.

To get from where we are now through the NERVA program to the RIFT (Reactor In Flight Test) will require advance on all fronts, but the materials aspect of the work will no doubt, in the end, set the boundary to what can be accomplished.

KIWI-B CONTROL SCHEMATIC
AUTOMATIC PROGRAMMED OPERATION

Figure 4

Fig. 3 View of Fifth Whim Before Assembly.

Figure 2

Cutaway section of Kiwi-A

Figure 1

Experimental tension creep curves showing the effects of stress (reduced) and temperature on graphite containing 1/4 gram U/cc. Reduced stress means stress/breaking stress.