ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois

STUDY OF THE PACKED-BED FUEL ELEMENT CONCEPT

by

M. B. Rodin

Reactor Engineering Division

Contributions by:

W. B. Loewenstein
D. R. MacFarlane
J. J. Santori
A. Smaardyk

August 1960

Operated by The University of Chicago
under
Contract W-31-109-eng-38

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	5
I. INTRODUCTION	5
II. CONCEPTUAL DESIGN CRITERIA	7
A. Description of a Conceptual Fuel Element Design	7
B. Design Criteria	8
III. REACTOR MATERIALS	10
A. General	10
B. Fuels	10
C. Structural	15
D. Solid Mechanics	23
E. Corrosion	26
F. Erosion	27
G. Radiation Effects	28
IV. HEAT TRANSFER AND FLUID FLOW	30
V. REACTOR CONCEPTS USING PACKED-BED FUEL ELEMENTS	41
A. General	41
B. He-UO ₂ Fast Reactor Concept	42
C. UC-H ₂ Reactor Concept	45
VI. CONCLUSIONS	48
VII. RECOMMENDATIONS	50
NOMENCLATURE	51
REFERENCES	54

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Geometric Relationships and Porosity of Various Sphere Packings	12
2.	Physical and Thermodynamic Properties of Refractory Metals	16
3.	Properties of Refractory Oxides	17
4.	Physical Properties of the Refractory Sulfides	18
5.	Physical Properties of the Refractory Nitrides	19
6.	Physical Properties of the Refractory Carbides	20
7.	UO ₂ -He Reactor Concept Data	43-44
8.	UC-H ₂ Reactor Concept Data	46-47

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Fuel Assembly	7
2.	Schematic - Reactor	8
3.	UO ₂ -Al ₂ O ₃ Phase Equilibrium Diagram	11
4.	UO _{2-2.1} -MgO Phase Equilibrium Diagram	11
5.	UO ₂ -ZrO ₂ Phase Equilibrium Diagram	11
6.	UO ₂ -ThO ₂ Phase Equilibrium Diagram	11
7.	Particles Prepared in Denitration Fluidized Bed	13
8.	Tensile Strength of Some Refractory Metal Alloys (Density Compensated)	21
9.	Elevated-Temperature Tensile Strength of Various Purity Grades of Tantalum Metal	21
10.	Effect of Temperature on Impact Strength of Some Oxide Materials	21
11.	Short-Time Tensile Strength of Various High Temperature Materials	21
12.	Effect of Temperature on the Short-Time Strength of Several Oxide Materials	21

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
13.	Effect of Porosity on Creep Strength of Sintered Al_2O_3	22
14.	Effect of Grain Size on Strength of BeO	22
15.	Tensile Breaking Strength of Graphite	24
16.	Thermal Conductivity of Pyrographite as Compared to Polycrystalline Oxides vs Temperature	24
17.	Thermal Conductivity of Pyrographite, Copper and Graphite vs Temperature	24
18.	Strength to Weight Ratio vs Temperature for Various Materials	24
19.	Correlation of the Activation Energies and Melting Temperature	26
20.	Friction Factor vs Reynolds Number (Modified)	35
21.	Profile of Gas Pressure vs Bed Depth	36
22.	Gas Pressure vs Bed Depth	36
23.	Fractional Pumping Power, η vs Power Density, Q	36
24.	Fractional Pumping Power, η vs Mass Flow Rate, G	37
25.	Fractional Pumping Power, η vs Inlet Pressure, p	37
26.	Fractional Pumping Power, η vs Particle Diameter for Various Porosities	37
27.	Heat Transfer Coefficient vs Mass Flow Rate for Packed Bed	38
28.	Temperature Difference Between Gas and Solid for Packed Bed	39
29.	Relative Temperature Difference ($t_s - t_g$) vs Particle Diameter	39
30.	Pressure Drop Across Wall vs Flow Rate for Different Inlet Pressures	39

STUDY OF THE PACKED-BED FUEL ELEMENT CONCEPT

by

M. B. Rodin

ABSTRACT

A preliminary study on the application of packed-bed technology to the design of nuclear fuel elements is presented. The study is limited primarily to problems in materials, fluid flow and heat transfer, and to particles 50-300 microns in diameter. Factors affecting bed performance, such as particle size and shape, bed porosity, and system pressures, were studied. The report indicates that packed beds can be designed to operate at high temperature and high power density, and methods for calculating bed performance are provided. It appears that the containment of fission products within the particles in the sizes of interest would be difficult.

For purposes of illustration the study describes two potential reactor concepts, one for breeding and one for rocket propulsion. The breeder concept studied the use of a helium-cooled bed of 200-micron-sized UO_2 fuel particles; the coolant is heated from 150 to 980°C at which a peak fuel power density of 3.75 Mw/ℓ is achieved. The propulsion concept studied the use of a hydrogen-cooled bed of 200-micron-sized uranium carbide fuel particles; the coolant is heated from 93 to 2320°C, and a peak fuel power density of about 11 Mw/ℓ is reached. In addition, the studies show that the helium-cooled UO_2 bed can be operated as high as 8 Mw/ℓ of fuel for extended periods and the hydrogen-cooled UC bed can be operated as high as 50 Mw/ℓ, with 100-micron sized particles for short periods.

The study notes the highly empirical nature of theory in packed-bed technology and describes a program of research and development which is deemed necessary to provide data for use in designing packed-bed fuel elements for reactors.

I. INTRODUCTION

Based upon a survey and review on some of the work reported in the literature on porous media, a study and evaluation of some of the potentialities of the gas-cooled, packed-bed type fuel element was made.

The packed-bed fuel elements appear to offer significant advantages to reactors designed for high temperature and high power density operation. The packed-bed fuel element system is also amenable to use with liquid coolants: water or liquid metals. Because of the high power densities possible, the fuel element may lend itself to use with two-phase coolants, those which undergo change of state (i.e., liquid to gas) in passing through the bed. Studies on these applications are, however, beyond the scope of this report.

There are a number of applications where high power density or high-temperature gas effluent, or the combination of both, are desired. For rocket propulsion, high power densities and temperatures of 2200°C and up provide premium performance. Coal gasification processes, chemical fuel cells, thermionic devices, and some plasma thermocouples require temperatures of 1300°C and up for efficient operation. Systems using the magnetohydrodynamic principle for direct conversion of heat to electricity have been studied for operation at 2000°C using helium as coolant. High temperature is especially desirable for generation of power in space to reduce the size and weight of the equipment. High-temperature reactors, as a source of radiant energy, and high power density reactors, as a source of high neutron fluxes, may also prove useful. There may, of course, be chemical processes that are dependent on high temperature, high heating rates, or fission recoil particles which can be provided by this fuel element concept. Useful reactor lifetimes may vary from a few hundred seconds for rocket propulsion to years for space power applications.

This report, in general, is limited to studies on materials, heat transfer, fluid flow, and to particles 50-300 microns in diameter. A chapter describing two possible applications of the packed-bed fuel element, one for breeding and one for rocket propulsion, are included for purposes of illustration.

The design work was performed, as has been customary, in both English and metric units. All English units were later converted to the metric system. On some curves, both units are shown and, where convenient, units in the metric system may have been rounded.

II. CONCEPTUAL DESIGN CRITERIA

A. Description of a Conceptual Fuel Element Design

A simple packed-bed fuel element consists of a layer of fuel particles arranged in a holder to permit the coolant to flow through the

FIG. 1

bed of particles. Thin plates of porous media or wire screens may be used to support the bed. A reactor fuel assembly can be made by connecting a number of these elements to common inlet and outlet headers. Figures 1 and 2 illustrate a schematic arrangement of the fuel elements into a fuel assembly and a possible arrangement of the fuel assemblies in a core of a fast reactor. It is assumed throughout this report that the nuclear heating can be accomplished so that all calculations are reduced to the problem of removing the heat from the bed.

The use of porous media impregnated with fissile materials as a fuel element has considerable merit. The basic difference in concept between a packed bed, which is the subject of this report, and a porous fuel element is in degree rather than in concept, and certain analytical methods are applicable to both systems. The porous element may have a higher degree of physical stability and may in the future be manufactured to provide lower flow resistance

than that possible in a packed bed. A porous fuel element, however, is subject to irreparable fracture which can complicate control of the flow of coolant in the reactor.

FIG. 2

B. Design Criteria

The basic equation for convection heat transfer from a solid to a gas is:

$$Q = h A \Delta t_m$$

where

Q = power density, Mw/ ℓ or kw/cm³ of fuel

A = area density (or specific surface area), that is, the total surface area of particles in a given volume, cm²/cm³.

h = average heat transfer film coefficient between solid and gas, kw/(cm²)(°C)

Δt_m = mean temperature difference between the solid fuel and the gas, °C.

In order to achieve high values of Q , it is necessary that the product of the three right-hand terms be as large as possible. To achieve high gas temperatures, of course, it is necessary that the fuel surface be operated at high temperature.

The area density for spherical particles can be determined from the following equation:

$$A = 6(1 - \bar{X})/D_p \quad ,$$

where

$$\begin{aligned} \bar{X} &= \text{porosity volume fraction of voids} \\ D_p &= \text{diameter of particle, cm.} \end{aligned}$$

A comparison between packed beds and plate-type elements is made to illustrate the advantage of the particle beds. The area density for a 200-micron diameter particle with a bed porosity of 0.4 is $180 \text{ cm}^2/\text{cm}^3$. Application of an arbitrary surface correction of 50%, for surface losses due to areas of contact and other irregularities as will be discussed later, results in a net value of $90 \text{ cm}^2/\text{cm}^3$. If a plate fuel element, 200 microns in thickness, were used with an equivalent porosity, the area density would be $50 \text{ cm}^2/\text{cm}^3$. However, a more realistic plate thickness would be of the order of 750 microns and with a porosity of 0.5; the area density would then be only $13.3 \text{ cm}^2/\text{cm}^3$. Thus, the packed-bed fuel element has an area density advantage of about seven over an equivalent plate-type element.

In regard to h , the heat transfer film coefficient, the calculations indicate that values for packed beds are substantially higher than those calculated for plate-type fuel elements and are probably due to the more tortuous and hence more turbulent flow of gas through the bed. Values for Δt_m shown in the report are lower than those achieved with plate-type fuel elements and are due to the high area densities of packed-bed elements, which permit the gas to approach very closely the temperature of the fuel particle in the bed. In addition, the temperature gradient in the fuel particle is very small compared to a heterogeneous plate of reasonable thickness. It is these differences between plates and particles that permit the achievement of high power densities and high coolant temperatures with the packed-bed fuel element.

High ratios of pumping power to heat output are generally associated with gas-cooled reactors. The magnitude of this value in this system is determined by the system pressure, particle size, bed thickness, and temperature rise of the coolant. It should be noted that although the resistance of the bed to gas flow may be higher than for plate-type fuel elements, the mass flow rate will be substantially lower because of the higher gas temperature rise possible in the bed because of this; by optimizing the values for particle size and bed thickness, relatively low net values for pumping power are possible.

III. REACTOR MATERIALS

A. General

The general design criteria for selecting materials for use as moderators, coolants, fuel, and structure for a particular reactor design are well known and will not be repeated here. Physical properties of some potential fuels and structural materials are tabulated in the report for information. Helium and hydrogen coolants are used for purposes of illustration in this study, although other gases can certainly be used. From a review of the tables, but with some exceptions of course, it can be seen that with regard to strength of materials, refractory metals and alloys are useful up to 1200°C; ceramics and cermets may be used up to temperatures of 2200°C; and graphite, carbon, and some carbides may be used over the temperature range from room temperature up to 3000°C. This temperature appears to be the upper limit of operation for convection-cooled systems using materials which are presently available. The use of materials at any temperature, of course, is necessarily qualified by such factors as compatibility with each other and time, if the material is subject to creep strength limitations. Some discussion reflecting problems of fabrication, corrosion, and other factors are mentioned.

B. Fuels

The report covers those uranium compounds for which a reasonable amount of information exists and which are readily available. Consideration for other uranium and plutonium compounds will develop as additional data, availability, and handling experience is accumulated.

Uranium dioxide (UO_2) is the most readily available fuel and one for which the greatest amount of information exists. It has very good high-temperature properties, and extensive engineering and test data are available. Further, it can be readily obtained from a number of different sources and to various specifications. For these reasons most references in this report are directed to the use of UO_2 .

The ThO_2 - UO_2 ceramic has also received substantial testing and is very stable in oxidizing atmospheres. ThO_2 has a high melting point, and the melting points of various compositions of the ThO_2 - UO_2 system are higher than for pure UO_2 . The phase diagrams⁽¹⁾ for the systems UO_2 - ThO_2 , UO_2 - MgO , UO_2 - ZrO_2 , and UO_2 - Al_2O_3 are shown in Figs. 3 to 6. Uranium monocarbide (UC) melts at a somewhat lower temperature, but has a high thermal conductivity.

FIG. 3
 $\text{UO}_2\text{-Al}_2\text{O}_3$ PHASE EQUILIBRIUM DIAGRAM.

FIG. 4
 $\text{UO}_2\text{-2.1-MgO}$ PHASE EQUILIBRIUM DIAGRAM.

FIG. 5
 $\text{UO}_2\text{-ZrO}_2$ PHASE EQUILIBRIUM DIAGRAM.

FIG. 6
 $\text{UO}_2\text{-THO}_2$ PHASE EQUILIBRIUM DIAGRAM

Pyrographite⁽²⁾ is an anisotropic form of graphite and exhibits thermal conductivity along one axis equal to that of copper and along another axis comparable to that of the best insulators. "Developments of alloys and compounds of uranium made with pyrographite may provide highly desirable characteristics."⁽²⁾

Other uranium compositions, such as the nitrides and sulphides, are also of interest.⁽³⁾ The fissioning of an oxide fuel atom will release O_2 which, for certain applications, may be undesirable. The use of nonoxide fuels eliminates this difficulty.

Table 1⁽⁴⁾ indicates various geometrical arrangements for spherical particle and the resulting porosities. Although the table indicates that bed porosities of 0.2595 to 0.4764 can be achieved, experimental data indicate that reproducible stable beds of spherical particles prepared by bulk handling methods usually result in beds with porosities between 0.38 and 0.42.

Table 1

GEOMETRIC RELATIONSHIPS AND POROSITY OF
VARIOUS SPHERE PACKINGS*

	Cubic	Ortho- rhombic	Rhombo- hedral	Ortho- rhombic	Tetragonal sphenoidal	Rhombo- hedral
Spacing of layers**	$r\sqrt{4}$	$r\sqrt{3}$	$r\sqrt{3}$	$r\sqrt{4}$	$r\sqrt{3}$	$r\sqrt{2/3}$
Tangent neighbors	6	8	12	8	10	12
Face angles	90°	90°, 60°- 120°	90°, 60°- 120°	90°, 60°- 120°	60°-120° 75° 31' 109° 29'	60°-120°
Interfacial angles	90°	90°, 60°- 120°	54° 44' 125° 16'	90°, 60°- 120°	90° 63° 26' 116° 34'	70° 32' 109° 28'
Porosity	0.4764	0.3954	0.2595	0.3954	0.3019	0.2595

*A partial listing of possible arrangements.

**The radius of the particle is denoted by r .

Hrubicek⁽⁵⁾ reports that stable beds having porosities up to 86% can be prepared by arching and bridging spherical particles, although uniform spacings between the particles are not achieved. Techniques for preparing these high-porosity beds are not given.

Work done by Seldin and Mrozowski⁽⁶⁾ on fixed granular beds, made by coating graphite particles with carbonaceous binders which are then baked to form rigid bodies, may offer a method for achieving high porosity bodies.

Figure 7 is a photograph of particles produced in a fluidized denitration bed. It is noted that the surfaces of some of the particles are covered by a random distribution of conical protrusions. Beds composed of these particles could also provide a method for achieving high bed porosities.

FIG. 7

PARTICLES PREPARED IN DENITRATION FLUIDIZED BEDS

Particle surfaces should be resistant to sintering. The sintering characteristics of particles are difficult to specify. In the manufacture of UO_2 pellets, for example, where substantial experience exists, attempts to establish specifications for sinterability have not been particularly successful. In addition to differences in material manufactured by different vendors, it is reported that the sintering characteristics of each lot of material received from the same vendor has to be established experimentally. It would appear, therefore, that the selection of materials for use as fuel particles will be subject to experimental testing.

The temperature at which particles sinter can be increased by a firing treatment. The firing treatment reduces the surface energy of the individual particles. For example, high-fired UO_2 , with or without pressure, may be heated to 1700°C before agglomeration or sintering can be detected.⁽⁷⁾ Sintering, however, can be detected in calcined UO_2 material at 500 - 700°C .

Particles may be made by a number of processes, some of which include crushing of larger pieces or using shot techniques in which the material is melted in plasma jets and sprayed into space, where the particles freeze in spherical shapes. There are also proprietary processes for producing small ceramic spheres.

Stoichiometric compositions of oxide fuel are required since either interstitial or surface-adsorbed oxygen when released on heating can affect the corrosion and strength properties of other materials in the system. Approximate stoichiometric compositions can be made by heating the fuel particles in either hydrogen or NaK. $\text{UO}_{2.04}$, which is commercially available, can be reduced to $\text{UO}_{2.003}$ by heating in H_2 at 900°C or to $\text{U}_{2.001}$ by heating in NaK at 500°C .

Separating particles of different sizes is most easily performed by screening. This method produces a product having a spectrum of sizes over a fairly narrow range. Particle sizes in the 200-micron diameter range if sifted between screens (either U.S. or Tyler mesh) will produce a cut of particles varying about $\pm 10\%$ in diameter. Air elutriation methods can provide batches of particles with smaller diametrical tolerances.

The particle diameter is only a nominal indication of size, since fuel particles are not necessarily perfectly smooth and spherical. Sometimes a sphericity factor ψ is introduced in the calculations, where ψ is the ratio of the surface area of a perfect sphere to the surface area of the particular particle. Fuel costs are favorably influenced by liberal tolerances which must be balanced against potential losses in performance.

The bulk densities of fuel particles vary in accordance with the method of preparation and arrangement. The theoretical density of UO_2 ,

for example, is 10.96 gm/cm^3 , but the bulk density of a bed of particles will vary from 4 to 6.5 gm/cm^3 using normal handling techniques (porosity 0.38-0.42). This variation in bulk density can be due to (a) irregularities in particle arrangements, (b) voids in the particles, and (c) variations in particle size and sphericity.

The application of thin nonreactive refractory coatings to particles could beneficially suppress the sintering characteristics of a particle, reduce spallation, fuel evaporation losses, and fission product release. Very thin films of refractory coatings are reported to have been successfully applied to ceramic particles by means of vapor deposition or plating techniques. Other coating methods may also be applicable.

C. Structural

In designing such components as fuel holders, gas ducts, support plates, and vessels, it is necessary that these members have sufficient strength at the design temperature to provide for the thermal, mechanical forces, weight and fluid stresses present in the system, and that as few parts of the system as possible be exposed to high temperature gas.

The schematic shown in Fig. 1 is a conceptual high-temperature fuel element design which might be developed. The fuel particles, which are the hottest material in the system, are supported by the bed screen. Since the fuel particles are at a temperature somewhat above that of the coolant, they may, therefore, raise the screen to that temperature. The balance of the components in the fuel assembly, with the exception of the outlet ducts which are at the coolant outlet temperature, are either at the inlet gas temperature or some intermediate temperature. An inert granular material having low thermal conductivity may be interposed between the bed and the screen so that the temperature of the screen can be limited to the temperature of the coolant. The benefit derived from this small difference at high temperature, however, may be significant. The outlet ducts resist the fluid and thermal stresses and need not support the weight of the elements.

Tables 2-6 and Figs. 8-12 indicate physical and thermal properties of potential structural materials⁽³⁾ and can serve as a guide for developing conceptual designs. Many of the published values for these properties vary substantially, and high-temperature measurements also are not made with the precision commonly achieved at the lower temperatures. Allowances in design must be made for these uncertainties.

Figures 13 and 14 show that the strength is adversely affected by crystal size and porosity⁽³⁾ of a material. Data are presented for a specific material, but are representative of the problem. Many useful high-temperature materials are made by sintering processes in which porosity and crystal size can vary.

Table 2

PHYSICAL AND THERMODYNAMIC PROPERTIES OF REFRACTORY METALS

Property	Metals								
	Tungsten	Rhenium	Osmium	Tantalum	Molybdenum	Columbium	Hafnium	Vanadium	Chromium
Melting point, °C	3410	3180	3000	2996	2610	2415	1975	1900	1875
Boiling point, °C	6700	5630	5500	6100	4800	3300	5400	3350	2469
Crystal structure ^a	BCC	HCP	HCP	BCC	BCC	BCC	HCP ^b	BCC	BCC
Density, g/cm ³	19.3	21.0	22.5	16.6	10.2	8.56	13.36	6.11	7.20
Thermal conductivity, cal/cm ² /cm/C/sec	0.48	0.17	-	0.13	0.35	0.125	0.053	0.074	0.16
Electrical resistivity, microhm-cm at 20°C	5.5	19.3	9.5	13.5	5.21	14.8	30	24.8	12.8
Specific heat, cal/g at 20°C	0.032	0.033	0.031	0.033	0.061	0.065	0.035	0.119	0.107
Coefficient of linear expansion, 10 ⁻⁶ /°C, near 20°C	4.5	6.7	6.6	6.6	5.4	7.1	6.0	9.7	6.2

^a BCC designates body-centered cubic; HCP designates hexagonal close packed; FCC designates face-centered cubic.

^b HCP lattice transforms to BCC at 1310°C.

Table 3

PROPERTIES OF REFRACTORY OXIDES

	Composition	Fusion Temp (°C)	Max Normal Use Temp (°C)	Density, [Bulk (b), True (t)] (gm/cc)	Linear Expansion (10 ⁻⁶ in/in/°C) 20-1000°C	Modulus of Rupture (MR) or Tensile Strength (TS) (psi)		Modulus of Elasticity (10 ⁶ psi)	Thermal Stress Resistance
						at 20°C	at 1000°C		
Sapphire crystal	99.9 Al ₂ O ₃	2030	1950	3.97(t)	8.6	40,000-150,000 (MR)	30,000-100,000 (MR)	55	Very good
Sintered alumina	99.8 Al ₂ O ₃	2030	1900	3.97(t)	8.6	30,000 (MR)	22,000 (MR)	53	Good
Sintered beryllia	99.8 BeO	2570	1900	3.03(t)	8.9	20,000 (MR)	10,000 (MR)	45	Excellent
Sintered calcia	99.8 CaO	2600	2000	3.32(t)	13.0	-	-	-	Fair-poor
Chrome-alumina cermet (Haynes-Stellite LT-1)	77 Cr, 23 Al ₂ O ₃	1850	1300	5.9 (b)	8.9	45,000 (MR)	20,000 (MR)	37.5	Excellent
Sintered magnesia	99.8 MgO	2800	1900	3.58(t)	13.5	14,000 (MR)	12,000 (MR)	30.5	Fair-poor
Sintered mullite	72 Al ₂ O ₃ , 28 SiO ₂	1800	1750	3.03(t)	5.3	12,000 (MR)	7,000 (MR)	21	Good
Sintered forsterite	99.5 Mg ₂ SiO ₄	1885	1750	3.22(t)	10.6	10,000 (MR)	-	-	Fair-poor
Sintered spinel	99.8 MgAl ₂ O ₄	2135	1850	3.58(t)	8.8	12,300 (MR)	11,000 (MR)	34.5	Fair
Sintered titania	99.5 TiO ₂	1840	1600	4.24(t)	8.7	8,000 (MR)	6,000 (MR)	-	Fair-poor
Sintered thoria	99.8 ThO ₂	3050	2500	10.50(t)	9.0	12,000 (MR)	7,000 (MR)	21	Fair-poor
Sintered yttria	99.8 Y ₂ O ₃	2410	2000	4.50(t)	9.3	-	-	-	Fair-poor
Sintered urania	99.8 UO ₂	2800	2200	10.96(t)	10.0	12,000 (MR)	18,000 (MR)	25	Fair-poor
Sintered stabilized zirconia	92 ZrO ₂ , 4 HfO ₂ , 4 CaO	2550	2200	5.6 (t)	10.0	20,000 (MR)	15,000 (MR)	22	Fair-good
Sintered zircor	99.5 ZrSiO ₄	2420	1800	4.7 (t)	4.2	12,000 (MR)	6,000 (MR)	30	Good
Silica glass	99.8 SiO ₂	1710	1100	2.20(t)	0.5	15,500 (MR)	-	10.5	Excellent
Mullite porcelain	70 Al ₂ O ₃ , 27 SiO ₂ , 3 MO + M ₂ O	1750	1400	2.8 (b)	5.5	10,000 (MR)	6,000 (MR)	10	Good
High alumina Porcelain	90-95 Al ₂ O ₃ , 4-7 SiO ₂ , 1-4 MO + M ₂ O	1800	1500	3.75(b)	7.8	50,000 (MR)	-	53	Very good

Table 4

PHYSICAL PROPERTIES OF THE REFRACTORY SULFIDES

	Melting Point (°C)	Density (g/cm ³)	Electrical Resistivity (ohm-cm)	Thermal Expansion Coefficient (10 ⁻⁶ /°C)	Hardness (kg/mm ²)
CeS	2450	5.93	90 x 10 ⁻⁶	9.8	-
ThS	>2200	9.57	<10 ⁻⁴	-	-
BaS	>2200	4.25, 4.33	Insulator	-	-
Nd ₂ S ₃	2200	5.34	-	-	-
HfS	2100-2200(est)	-	-	-	-
La ₂ S ₃	2110-2150	4.85, 5.01	-	-	-
Zr ₄ S ₃	2050-2150(est)	-	-	-	-
TiS	2000-2100	4.05	-	-	-
Ce ₃ S ₄	2050	5.3	400 x 10 ⁻⁶	-	-
US	2010	10.87	Conductor	-	-
BeS	>2000	2.36	-	-	-
Th ₄ S ₇	2000	7.78	10 ⁻⁴ to 10 ⁻³	-	-
U ₂ S ₃	>2000	8.81	Conductor	-	-
SrS	>2000	3.64, 3.67	-	-	-
MgS	>2000	2.85	Insulator	-	-
Th ₂ S ₃	1950	7.88	10 ⁻⁴ to 10 ⁻³	-	-
Y ₂ S ₃	1900-1950	-	-	-	-
ThS ₂	1905	7.36	Insulator	-	-
Sm ₂ S ₃	1900	5.73	-	-	-
Ce ₂ S ₃	1890	5.19	>10 ³	13.2	4.50
US ₂	1850	7.90	Insulator	-	-
VS	1800-2000	4-4.4	-	-	-

Table 5

PHYSICAL PROPERTIES OF THE REFRACTORY NITRIDES

	Melting Point (°C)	Density (g/cm ³)	Electrical Resistivity (ohm-cm)	Thermal Conductivity (cal/cm sec °C)	Thermal Expansion Coefficient (10 ⁻⁶ /°C)	Hardness* (kg/mm ²)
			(a) <u>Metallic</u>			
HfN	3310	14.0	Cond	-	-	-
TaN	3100	14.1	135 x 10 ⁻⁶	-	-	(8)
ZrN	2980	7.32	13.6 x 10 ⁻⁶	0.040	6 to 7	1510(8)
TiN	2950	5.43	21.7 x 10 ⁻⁶	0.070	-	1770(8 to 9)
ScN	2650	4.21	-	-	-	-
UN	2650	13.52	-	0.011	-	-
ThN	2630	11.5	-	-	-	-
Th ₃ N ₄	2360	-	-	-	-	-
NbN	2050(dec)	7.3	200 x 10 ⁻⁶	-	-	(8)
VN	2030	6.04	85.9 x 10 ⁻⁶	-	-	-
CrN	1500(dec)	6.1	-	-	-	-
			(b) <u>Nonmetallic</u>			
BN	3000(dec)	2.27	>10 ¹³	0.04-0.12	0.05-10	100(1.2)
AlN	2400(subl)	3.05	>10 ¹¹	0.048-0.072	4.03-6.09	1200(7+)
Be ₃ N ₂	2200	-	-	-	-	-
Si ₃ N ₄	1900(subl)	3.44	1.43 x 10 ³	0.045	2.47	-

*Hardness values in parenthesis are on Mohs scale of hardness.

Table 6

PHYSICAL PROPERTIES OF THE REFRACTORY CARBIDES

	Melting Point (°C)	Density (g/cm ³)	Electrical Resistivity (ohm-cm)	Thermal Conductivity (cal/cm sec °C)	Thermal Expansion Coefficient (10 ⁻⁶ /°C)	Hardness (kg/mm ²)
			(a) <u>Metallic</u>			
HfC	3887	12.20	109 x 10 ⁻⁶	-	-	2910
TaC	3875	14.48	30 x 10 ⁻⁶	0.053	6.61	1800
ZrC	3530	6.70	63.4 x 10 ⁻⁶	0.049	6.93	2600
NbC	3500	7.82	74 x 10 ⁻⁶	0.034	6.84	2400
Ta ₂ C	3400	15.1	-	-	-	1000
TiC	3250	4.7	68 x 10 ⁻⁶	0.041	7.61	2500
VC	2830	5.36	156 x 10 ⁻⁶	-	-	2800
W ₂ C	2730	17.20	81 x 10 ⁻⁶	-	5.9	3000
MoC	2692	8.4	49 x 10 ⁻⁶	-	-	-
Mo ₂ C	2687	8.9	97.5 x 10 ⁻⁶	-	-	1800
ThC ₂	2655	9.6	-	-	-	-
WC	2630(dec)	15.50	12 x 10 ⁻⁶	-	6.1	2400
ThC	2625	10.65	-	-	-	-
UC ₂	2450	11.28	-	0.079	12.5	-
UC	2350	13.63	-	0.20	-	-
Cr ₃ C ₂	1895	5.6	-	-	8.8-11.0	1300
			(b) <u>Nonmetallic</u>			
SiC	2830(dec)	3.21	0.1-10 ¹²	0.10	4.3-4.5	2480
Al ₄ C ₃	2800	2.99	-	-	-	-
B ₄ C	2450	2.51	0.3-0.8	0.07-0.2	4.5	2750
Be ₂ C	2150(dec)	2.26	0.063	0.05	10.5	2410

FIG. 8
TENSILE STRENGTH OF SOME REFRACTORY METAL
ALLOYS. (DENSITY COMPENSATED)
(METRIC UNITS IN PARENTHESES)

FIG. 10
EFFECT OF TEMPERATURE ON IMPACT STRENGTH OF SOME
OXIDE MATERIALS. (METRIC UNITS IN PARENTHESES)

FIG. 12
EFFECT OF TEMPERATURE ON THE SHORT-TIME STRENGTH OF SEVERAL
OXIDE MATERIALS. (METRIC UNITS IN PARENTHESES)

FIG. 9
ELEVATED-TEMPERATURE TENSILE STRENGTH OF VARIOUS
PURITY GRADES OF TANTALUM METAL
(METRIC UNITS IN PARENTHESES)

FIG. 11
SHORT-TIME TENSILE STRENGTH OF VARIOUS HIGH TEMPERATURE
MATERIALS. (METRIC UNITS IN PARENTHESES)

FIG. 13

EFFECT OF POROSITY ON CREEP STRENGTH OF SINTERED Al_2O_3
(METRIC UNITS IN PARENTHESES)

FIG. 14

EFFECT OF GRAIN SIZE ON STRENGTH OF BeO
(METRIC UNITS IN PARENTHESES)

Graphite has unusually desirable high-temperature properties. The structural properties of graphite, as indicated in Figs. 15-18, improve with temperature to about 2700°C.

The porosity of ordinary graphite normally varies between 14 and 20% and can be varied over greater ranges by controlling the manufacturing processes. Thus the porosity of porous graphite can be increased over 50%. Methods for manufacturing impervious graphite are being developed. Recent work using furfural alcohol impregnation to plug the pores is reported to have reduced the permeability of fine-grained graphite from $1 \times 10^{-2} \text{ cm}^2/\text{sec}$ to $5 \times 10^{-9} \text{ cm}^2/\text{sec}$. This latter rate is sufficiently low to permit consideration of graphite for impervious applications. Pyrographite is also reported to be available in impervious quality. Graphite has a high strength-to-weight ratio which is a decided advantage, since the weight of materials, at high temperature, can add appreciably to the total stress in the member. Carbides of niobium, tantalum, and tungsten are reported to have good resistance to hydrogen at high temperature.

D. Solid Mechanics

Thermal stresses and temperature gradients generated in particles in the diameters of interest should be relatively small.

The temperature gradient across a sphere can be calculated from the equation

$$\Delta t = Q r^2 / 6k_t \quad ,$$

where

Δt = temperature difference between surface and center of particle,
 Q = volumetric heat generation rate
 r = particle radius

and

k_t = thermal conductivity.

At a power density of 8 Mw/ℓ of fuel, the temperature rise Δt in a particle 200 microns in diameter is a few degrees ($\sim 2^\circ\text{C}$).

The thermal stress in a spherical particle can be calculated from the equation

$$\sigma = \phi E Q r^2 / 6 k_t (1 - e) \quad ,$$

FIG. 15
TENSILE BREAKING STRENGTH OF GRAPHITE
(METRIC UNITS IN PARENTHESES)

FIG. 16
THERMAL CONDUCTIVITY OF PYROGRAPHITE AS
COMPARED TO POLYCRYSTALLINE
OXIDES VS. TEMPERATURE

FIG. 17
THERMAL CONDUCTIVITY OF PYROGRAPHITE, COPPER AND GRAPHITE
VS. TEMPERATURE. (METRIC UNITS IN PARENTHESES)

FIG. 18
STRENGTH TO WEIGHT RATIO VS. TEMPERATURE FOR VARIOUS
MATERIALS. (METRIC UNITS IN PARENTHESES)

where

σ = thermal stress
 ϕ = coefficient of expansion
 E = Young's modulus

and

e = Poisson's ratio.

At 1700°C, the tensile strength of UO_2 is reported to be about 350 kg/cm².⁽³⁾ The thermal stress is then calculated to be ~ 0.3 kg/cm².

If, however, agglomeration or sintering of particles occurs, then the central particle temperature and stresses in the agglomeration can become significant. Fuels having high thermal conductivity will be less affected. The behavior of an agglomeration of particles would be difficult to determine since the cumulative effect of irregular shape, perturbed cooling, and creep are not conducive to accurate calculations. Allowance for this possibility normally is included in the hot channel or safety factor.

A first approximation for estimating creep rate in metals⁽³⁾ is expressed by the relationship

$$\epsilon_0 = k e^{-(Z/RT)}$$

where

ϵ_0 = creep rate
 R = universal gas constant
 T = absolute temperature
 Z = activation energy for the creep process

and

k = constant.

The equation indicates that creep rate varies inversely with the activation energy and that the latter can be correlated with the melting point. Figure 19 presents some values for activation energies. This equation is useful as a guide for metals only.

Work on cermets and ceramics is less well developed. For example, some data on UO_2 may be of interest since UO_2 , in addition to being a fuel, may also be useful as a structural material. It is reported that the creep rate in bars of sintered $\text{UO}_{2.06}$ and $\text{UO}_{2.16}$ is the same at 800°C as the creep rate in $\text{UO}_{2.00+}$ at 1600°C. This reflects the well-known,

FIG. 19
CORRELATION OF THE ACTIVATION
ENERGIES AND MELTING TEMPERATURE

but not understood, effect of excess O_2 in sintered materials. There are many uses for oxide and metal structural materials made by sintering and where excess O_2 may be present. Thus, the problem of excess O_2 in materials is doubly deleterious both from a strength and from corrosion aspect, as will be discussed next.

E. Corrosion

The possible loss of fuel and structure by evaporation and mass transport of corrosion products is of fundamental importance in the design and operation of a high-temperature, gas-cooled reactor, especially where unclad fuels are being used. At the higher temperatures of interest, the vapor pressure of some uranium compounds may become significant. For

example, the vapor pressure of UO_2 at $1700^\circ C$ is 1.4×10^{-6} atmos and increases with temperature.

An example of the mass transport problem in structural and fuel material is now described. Helium and graphite (carbon) are compatible and do not react with each other. However, if oxygen is present as a contaminant, it will react with the carbon in the core to form gaseous CO and CO_2 , and these gases when circulated to the heat sink in the reactor system will deposit carbon and release O_2 for recirculation. The continuous loss of carbon from the core as well as the deposition of carbon in the heat removal sections of the system is undesirable. The presence of water vapor, which may behave either as a hydrolyzing agent or as a source of hydrogen and oxygen, will also aggravate the corrosion problem.

The mass transfer effect which occurred with carbon and O_2 can occur with the UO_2 and O_2 .⁽⁸⁾

The oxidation mechanism for UO_2 is believed to occur as follows:

The equation for the partial pressure of UO_3 (gas) in equilibrium with U_4O_9 is

$$\log p_{\text{UO}_2} = \left(\frac{3}{8}\right) \log p_{\text{O}_2} + \frac{\left(\frac{1}{4}\right) \Delta F^\circ(\text{U}_4\text{O}_9)_s - \Delta F^\circ(\text{UO}_2)_g}{RT},$$

where

ΔF° = free energy of activation

R = universal gas constant

T = absolute temperature

and

p = partial pressure.

At 1200°C, the partial pressure of O_2 in equilibrium with U_4O_9 is about 10^{-3} atm. Then,

$$p_{\text{UO}_2} = 6.19 \times 10^{-4} \text{ mm Hg}.$$

The loss of uranium from the bed to the coolant under these conditions is given by the equation

$$\frac{W}{V} = \frac{p}{RT} = 1.6 \times 10^{-6} \text{ g/l},$$

assuming equilibrium is reached.

The oxidation reaction may, of course, be inhibited by reducing the O_2 impurity in the coolant by gettering, coating the particle with a protective or sacrificial layer, or stabilizing the UO_2 with additives to form a more oxidation-resistant solid solution. It is believed that the oxidation rates for UO_2 can be reduced by a factor of 10^3 to 10^5 , using one or a combination of these techniques.

The corrosion resistance of some materials is dependent upon the formation of an adherent coating resulting from the reaction of the material and the coolant. Such coating may be damaged when subjected to bombardment by fission recoils, which will be present with the use of unclad fuels.

F. Erosion

The amount of material eroding from the fuel and structure during operation is difficult to calculate and will therefore have to be determined by experience. Erosion is sensitive to a number of variables, such as the abrasiveness and motion of the particles in the bed, the velocity of entrained solids in the coolant, the geometrical arrangement of

the system, physical properties of the structural materials, and temperature and mode of operation. For closed primary circuits, it appears that continuous filtering devices will be required in the external piping systems to remove (and to recover) the eroded fuel from the gas stream. The fineness of filtration required would, to a certain extent, depend upon the characteristics of the bed. Thus, the upper size limit for eroded products permitted to remain in the gas stream will depend upon the ability of these products to pass through the particular bed without being trapped and causing plugging.

Limited trapping of erosion products in the bed could also serve as a method for equalizing pressure drop between beds in a reactor core. Some tests were performed in the laboratory to measure attrition losses in one-centimeter thick beds. Insofar as could be determined, the precision of measurement being one in a thousand, no losses were experienced in extended runs using UO_2 particles, 200 microns in diameter, and helium coolant at modest velocities. It is expected that the large difference in density between the gas and particles minimizes any possibility of mechanical movement between the particles and hence any tendency to generate abrasion products.

G. Radiation Effects

A survey of the literature does not reveal any direct information on radiation effects on loosely packed fuel particles irradiated in inert atmospheres and at closely controlled temperatures. The literature does contain information on radiation damage to sintered pellets, on powder-filled capsules and powders swaged in tubes to high density. These data, however, are not particularly applicable.

The effect of neutron irradiation will be reflected in the dimensional stability of the particle. The effect may be reflected as fracture, spallation, surface roughening, and changes in sphericity of the particle. The magnitudes of these factors, depending upon fuel particles used and the duration and temperature of operation, can influence the ability of the coolant to flow uniformly through the bed and the generation of particle fines.

Fractures and spallation can result from stresses generated in the fuel body. Stresses in a particle result from a number of sources, such as temperature gradients, mechanical force, internal fission gas pressures, and retained fission products. As previously mentioned, temperature gradients in fuel particles in the sizes of interest are small.

The decrease in thermal conductivity normally associated with irradiation should not make any appreciable difference.

Since the individual particles will be supported in the fuel holders, the individual particle should not be subjected to mechanical forces.

Data on fission product release from UO_2 are available. The diffusion of gaseous and volatile fission products out of UO_2 depends primarily on the temperature of the fuel and the decay constant of the particular isotope. An approximation for the release of the long-lived isotope (half-life greater than 10 days) is given by the following equation:

$$F = 3.5 \times 10^{-5} (1/\lambda)^{0.33} ,$$

where

F = fractional escape of nuclide

and

λ = decay constant in sec.^{-1}

For UO_2 at temperatures above 1000°C , the fractional escape of each isotope will be increased by about a factor of 3 to 4 for each 100°C increase in temperature. In regard to radioactivity level in the primary system, assuming that the volatile and gaseous products (cesium, iodine, krypton, xenon, etc.) all diffuse out of UO_2 at the same rate, the total activity in a primary system will be about 0.06% of the total activity generated in the fuel, or 3×10^{-3} curie/watt of reactor power.

Some data exist on the plating-out characteristics of fission products. In one experiment, heated air was passed over an active sample of uranium; it was found that most of the tellurium and ruthenium tended to plate out on the ducting, with lesser amounts of the total strontium present. The data on the plating characteristics of iodine and bromine were erratic. At high temperature, however, some of these fission products should remain in the gaseous state and could be removed at chosen points in the system.

The range of fission recoils in uranium is estimated to be between 10 and 100 microns, and between 2 and 4 cm in gases. Thus, the number of fission recoils ejected from a particle will depend upon the size of the particle, and it is obvious that the yield will be rather high for the smaller particles. It further indicates that the use of particle coatings to suppress the release of fission product must be greater than 100 microns in thickness.

There has been some concern regarding sticking or "stitching" together of materials subject to fission recoil bombardment. Although this effect has been suspected, it has never been confirmed.

IV. HEAT TRANSFER AND FLUID FLOW

There is a substantial amount of information and a variety of solutions in the literature for determining fluid flow in packed beds with and without the transfer of heat. Solutions to fluid flow and heat transfer problems in packed beds are sensitive to the particular system, particle shape, and the fluid for which they were developed. Most solutions depend upon the use of empirical corrections. Therefore, caution must be exercised if equations or data are applied to conditions other than those for which they were originally established.

It is generally accepted that laminar flow in packed beds is present at low flow velocities and that the change to turbulent flow with increasing fluid velocity is a gradual process and occurs over a range of velocities. One investigator has placed the change from laminar to turbulent flow at a Reynolds number as low as in the range from 0.32 to 0.64. Some investigators, however, claim, because of the tortuous passage of flow between the interstices of particles, that only turbulent flow can exist. Other investigators state that since a bed is in reality a multichannel body, there will always be some laminar flow through some channels. In addition, there is some question regarding the effect of particle sphericity on fluid flow, some investigators stating that it is not particularly important. However, these differences may be accounted for on the basis that most investigators worked with different systems.

The Reynolds number is usually expressed by the equation

$$Re = GD/\mu \quad ,$$

where D, the hydraulic term, is the diameter of the tube, G is the mass flow rate, and μ the viscosity. For flow in packed beds, D_p , the particle diameter, is substituted for D, and the equation

$$Re' = GD_p/\mu$$

is referred to as giving a modified Reynolds number.

Basically, although there are a number of variations, there are four general methods^(11,12,13) used for calculating laminar fluid flow in packed beds. The Darcy method is based upon the concept of permeability. The Hagen-Poiseuille equation is based on the concept of converting the voids in the bed into an array of parallel capillary tubes, the diameter of the capillary tubes being a function of the particle size. The third method, developed independently by Kozeny and Hatch,⁽¹¹⁾ is based upon the particle size and bed porosity. For many engineering applications, it has been found practicable to establish a curve, plotting a friction factor term as the ordinate and a modified Reynolds number as the abscissa. Once established, the curve may then be used to solve flow problems for both laminar and turbulent conditions.

The Darcy equation for laminar flow can be expressed as follows:

$$v = PA_1(p_1 - p_2)/\mu L$$

where

P = permeability coefficient

L = depth of bed

v = superficial rate of fluid flow

p₁ = inlet pressure

p₂ = outlet pressure

μ = viscosity of fluid

and

A₁ = area of bed.

The Hagen-Poiseuille equation can be written as

$$v = \pi D_c^4 \Delta p / 128 \mu L \quad ,$$

where

D_c = diameter of the capillary tube

and

$$\Delta p = p_1 - p_2.$$

The Kozeny equation can be expressed as follows:

$$v = \frac{k A_1 \bar{X}^3}{\mu (1 - \bar{X})^2} \cdot D_p^2 \cdot \frac{\Delta p}{L} \quad ,$$

where

k = a constant.

Equations for turbulent flow usually contain two terms in which the viscous effect and the kinetic effects are expressed by separate terms. Laminar flow can be modified for turbulent conditions.

As an example, Darcy's equation has been modified by adding a second-order velocity (square) term as shown below and used to solve problems for turbulent flow:

$$\frac{\Delta p}{L} = k_1 \left(\frac{v}{A_1} \right) + k_2 \left(\frac{v}{A_1} \right)^2 \quad ,$$

where k₁ and k₂ are constants.

A study by D. MacFarlane outlined a method for calculating the performance of packed beds. The study was based on a simple model of a bed, one square foot in cross section and L feet in depth, in which the fission heat was uniformly generated. It was further assumed that all of the heat was removed by the gas and that there were no conduction or radiation losses from the surface or through the bed.

Bernouilli's equation in differential form is

$$-\frac{dp}{\rho} = (d\ell)\bar{w}_f \quad ,$$

where

$$\begin{aligned} dp &= \text{change in pressure} \\ \rho &= \text{density} \end{aligned}$$

and

$$(d\ell)\bar{w}_f = \text{pressure loss due to friction}$$

(neglecting the velocity and static head losses which are small for packed beds).

Define a friction factor term as

$$f = 2g_c D_p (dp/dx) / v^2 \rho \quad ,$$

where

$$\begin{aligned} g_c &= \text{gravitational constant} \\ v &= \text{superficial gas velocity} \end{aligned}$$

and

$$x = \text{fractional depth of bed.}$$

The modified Reynolds number is given by

$$Re' = D_p G / \mu$$

where

$$Re' = \text{Modified Reynolds number}$$

and

$$G = v\rho = \text{mass flow rate.}$$

The equation for gas temperature at any depth x in the bed is given by

$$t_g = t_{g1} + \frac{Q}{Gc_p} x \quad ,$$

where

c_p = specific heat of gas

t_g = temperature of the gas

and

t_{g1} = inlet temperature of the gas.

A temperature viscosity correction to the function factor term may be defined as

$$f' = \alpha + \beta (x/L)$$

where α and β are empirically determined constants.

From these equations and the assumption of ideal gas behavior there results

$$p_2^2 = p_1^2 - \frac{G}{D_p} \left[aGx + \left(b \frac{G}{L} + mQ \right) x^2 + n \frac{Q}{L} x^3 \right] ,$$

which may be simplified by assuming a constant f across the bed (a reasonable approximation if f does not vary by more than 50%) to

$$p_2^2 = p_1^2 - \frac{f_{av}G}{g_c D_p} \left[\kappa G x + \frac{\chi Q}{2} x^2 \right] ,$$

where

p_1 = initial pressure

p_2 = final pressure

$a = \alpha \kappa / g_c$

$b = \beta \kappa / 2g_c$

$m = \alpha \chi / 2g_c$

$n = \beta \chi / 3g_c$

$\kappa = RT_0/M$

$\chi = R/Mc_p$

T_0 = initial gas temperature (absolute)

M = molecular weight of the gas

and

R = universal gas constant.

The equation for determining the ratio of pumping work to total power is

$$\eta = \frac{w}{p} = \frac{GRt_{gav}}{MQLC} \log \frac{p_1}{p_2} ,$$

where

η = fraction of pumping power to total power output
 C = factor for error introduced by using t_{gav} in the formula
 w = work of pumping gas

and

$$p = QL.$$

It may also be shown that

$$t_{s(max)} = t_1 + \frac{Q}{Gc_p} L + \frac{Q}{LA},$$

where

$t_{s(max)}$ = maximum surface temperature of particle
 t_1 = inlet gas temperature
 Q/Gc_p = temperature rise of gas passing through the bed

and

$$Q/LA = \text{temperature of film between gas and solid}$$

The heat transfer film coefficient was determined from a mass transfer equation (selected from the literature⁽¹⁷⁾ as the one most appropriate for this system):

$$j_h = (St)(Pr)^{2/3} = 0.585 (Re)^{-0.30},$$

where

$$St = \text{Stanton No.} = h/c_p G$$

$$Pr = \text{Prandtl No.} = c_p(\mu/k_t)$$

and

$$j_h = \text{mass transfer function.}$$

These equations were applied to a study of a packed bed of 200-micron diameter UO_2 particles having a sphericity of 0.8, and a bed porosity of 0.4 with helium coolant entering at 93°C and leaving at 1200°C at a system pressure of 40 atm. For the specific study, the calculations showed that a power density in the fuel of about 8 Mw/l can be achieved, allowing safety factors for agglomerations up to 10 particles, a 25% variation in heat generation and flow through the bed, and limiting the maximum particle surface temperature to 1700°C.

The effect on bed performance with changes in temperature particle size, bed porosity, and system pressure was also investigated.

In general, the curves indicated that the pumping power varied inversely with the particle size, system pressure, porosity of the bed, and gas temperature rise. Since the power density varies directly, but not in the same proportion, with pumping power, care must be exercised in establishing bed design parameters to achieve reasonable values of pumping power.

The friction factors were obtained from the solid curve shown in Fig. 20, based on work by Brownell and Katz⁽¹⁴⁾ for a particle diameter of 200 microns, a particle sphericity of 0.8, and a bed porosity of 0.4. The curve was compared with a series of experimental measurements (individual points on Fig. 20) made by A. Smaardyck and J. Santori in the laboratory on 200-micron particles (nominal diameter) of commercial UO_2 and with helium at ambient temperature and low pressure, and found to be in reasonable agreement.

FIG. 20
FRICTION FACTOR VS. REYNOLDS NUMBER (Re')

*BY A. SMAARDYK AND J. SANTORI

Figure 21 shows the relationship between bed thickness and pressure profile for various power densities of fuel. Figure 22 shows the relationship between bed thickness and pressure profile for various mass flow rates. Figures 23-25 show the relationships between pumping power with mass flow rates, power density, bed thickness, and inlet pressures. Figure 26 reflects the effect of bed porosity and particle size on pumping power.

Variations of the heat transfer film coefficient with mass flow rates and gas outlet temperatures are shown in Fig. 27.

FIG. 21

PROFILE OF GAS PRESSURE VS. BED DEPTH
(METRIC UNITS IN PARENTHESES)

FIG. 22

GAS PRESSURE VS. BED DEPTH
(METRIC UNITS IN PARENTHESES)

FIG. 23

FRACTIONAL PUMPING POWER, η VS. POWER DENSITY, Q
(METRIC UNITS IN PARENTHESES)

FIG. 24

FRACTIONAL PUMPING POWER- η , VS. MASS FLOW RATE- G
 (METRIC UNITS IN PARENTHESES)

FIG. 25

FRACTIONAL PUMPING POWER, η , VS. INLET PRESSURE- P_1
 (METRIC UNITS IN PARENTHESES)

FIG. 26

FRACTIONAL PUMPING POWER, η , VS. PARTICLE DIAMETER
 FOR VARIOUS POROSITIES. (METRIC UNITS IN PARENTHESES)

FIG. 27

HEAT TRANSFER COEFFICIENT VS. MASS FLOW RATE FOR
PACKED BED. (METRIC UNITS IN PARENTHESES)

The temperature differences between the gas and solid for a range of mass flow rates and power densities are shown in Fig. 28. This calculation provides for a 50% area density correction factor, based upon a particle sphericity of 0.8, to allow for the packing and compacting of the particles. The correction is based upon work done by Bennett and Baumeister.⁽¹⁵⁾ The relationship between the gas temperature difference with particle size and porosity is shown in Fig. 29.

Figure 30, which is also applicable to packed beds, shows the relationship of temperature, mass flow rate, and pressure drop in a uniformly heated porous graphite element.⁽¹⁶⁾ It is noted that the pressure difference curve falls and then rises with increasing mass flow rate and decreasing temperature.

The minimum point on the curve has been interpreted as indicating the change from laminar to turbulent flow with instability of flow being characteristic of flow in the laminar region.

FIG. 28

TEMPERATURE DIFFERENCE BETWEEN GAS AND SOLID
FOR PACKED BED. (METRIC UNITS IN PARENTHESES)

FIG. 29

RELATIVE TEMPERATURE DIFFERENCE
($t_s - t_g$) VS. PARTICLE DIAMETER

FIG. 30

PRESSURE DROP ACROSS WALL VS. FLOW RATE FOR DIFFERENT
INLET PRESSURES. (METRIC UNITS IN PARENTHESES)

If localized heating occurs in the laminar region, the temperature of the gas will rise, which will reduce the flow rate due to the increase of gas viscosity with temperature. The reduction in flow rate will lead to further heating and temperature rise in the fuel. This is an unstable condition. In the turbulent region, the flow rate varies with the pressure change to stabilize the temperature.

It is noted that the pressure drop in the packed bed is lower for equivalent flow rates than in this particular grade (grade 30) of porous graphite. The packed bed should, therefore, be less susceptible to flow instability at the lower flow rate.

Radiation losses from the bed to cooler portions of the reactor system and effects of gamma heating on the bed have not been included in this report. These effects may be significant in magnitude and should be included in a detailed study of a specific reactor system.

In addition, wall effects on flow have not been included. It is believed that this effect will be small for the particles and bed sizes of interest.

V. REACTOR CONCEPTS USING PACKED-BED FUEL ELEMENTS

A. General

The use of the packed-bed fuel element introduces some new problems into reactor design. Some brief, but certainly not all, comments regarding these new design features are listed in this preliminary report. It is evident that more thorough studies are required. Two fast reactor concepts are described: one a He-cooled, UO_2 -fueled, and the other a H_2 -cooled, UC-fueled system. The former has a potential application for power generation and breeding, and the latter for rocket applications. The details for using the nuclear heat follow conventional practices and are not discussed here. The fuel element and reactor schematic design shown in Figs. 1 and 2 are used for both concepts.

In thermal reactors, bed thickness will be particularly important, since the neutron disadvantage factor in the fuel bed will make it difficult to generate heat uniformly in a bed of reasonable thickness. It will also be necessary to surround the beds with moderator.

It may be useful to use stage heating in these systems. Stage heating involves passing the coolant through two or more beds in series before discharging it to the exit headers. A variation of stage heating can also be used to reduce peak gas velocities by dividing the exit flow from one bed to other beds connected in series before discharging to the exit header.

The temperature distribution in both the fast and thermal reactor systems can differ, depending upon the method of operation selected. If the system is designed for equal rates of gas flow to all beds, then the outlet gas temperature, assuming a cosine-type flux distribution, will be the average of exit temperatures from the individual beds; beds near the periphery of the core will discharge the colder gas into the exit gas stream. If the system is designed for constant exit gas temperature from all beds, it will be necessary to meter flow to each bed in accordance with the individual bed heat-generation rate. In this case, assuming a heat cell consists of the bed and a distributed proportion of inlet and outlet header volume, all heat cells in the core would have the same temperature distribution. Thus, the core would have a constant temperature profile.

Since the inlet gas is at a higher pressure than the exit gas, absolute tightness between the two systems is not required; the amount of leakage permissible would depend upon engineering considerations.

In arranging the subassemblies in the core, it is noted that there are inlet and outlet plenum chambers at the top and the bottom of the core. In this arrangement, the peak gas velocities in the headers are reduced by

half. Further, the high gas velocities in the headers are present only at the inlet of the header for incoming gas and at the exit for the heated gas, with the gas velocities decreasing to zero towards the midplane of the core. These peak velocities can be reduced by tapering the headers toward the core midplane.

To reduce neutron streaming, the beds can be staggered axially to reduce the symmetry of voids in the core.

B. He-UO₂ Fast Reactor Concept

A very brief study on the application of the packed-bed fuel element to the EBR-II core arrangement is shown for purposes of comparison. Power density in the core has been kept as close to EBR-II levels as possible, although temperature rise of the coolant is necessarily greater. The study is basically limited to problems in heat transfer and fluid flow. The study is based on the substitution of helium at 40 atm pressure and operating over a temperature range of 150 to 980°C for the sodium coolant and 200-micron sized UO₂ particle for metallic uranium fuel rods. Substitution of a different metal for structure is also probably necessary because of the higher outlet gas temperature. Further, for simplification, the study is limited to the core only on the assumption that if the packed-bed fuel element can perform satisfactorily in the core, it will perform adequately in the blanket. Separate coolant systems may be required to prevent mixing of enriched uranium fines from the core with depleted uranium fines from the blanket. The use of PuO₂ fuels, based upon current knowledge, should be practicable and may possibly eliminate the need for separate coolant systems for the blanket and core.

Based upon estimates by W. Loewenstein, the critical mass for an enriched uranium loading will increase by about 10% and the enrichment of the uranium from 50% to 90%, due to the higher temperature of operation and higher neutron leakage from the core, resulting from the absence of the sodium in the core. Thus, all breeding will be performed in the blanket. Cores for larger fast reactors can be diluted with U²³⁸ and provide internal breeding.

The elimination of sodium should improve breeding gain and the use of ceramic fuels should reduce breeding gain, resulting in a small net effect. More detailed studies are required to establish quantitative values.

In this study, a constant exit bed temperature was used; a ratio of maximum to minimum power density of 2 and a ratio of maximum to average power density 1.5 were assumed. The pressure drop across the fuel bed (1.27 cm thick) was determined from the curves. It was assumed that the pressure drop in the balance of the primary system could be held to values consistent with conventional gas-cooled reactors (~ 0.3 kg/cm²).

Thus, about 7.5% of the gross power generated is required for primary system pumping. The maximum surface temperature of the particle was estimated to be 1080°C.

From a study of the curves, it was deduced that substantially higher power densities and exit gas temperature, and hence higher performance, could be achieved using UO_2 fuel and helium coolant.

The data developed for the reactor concept are shown in Table 7.

Table 7

UO_2 -He REACTOR CONCEPT DATA

Core

Power output, Mw	50
Volume, ℓ	66
Critical mass, kg	
U^{235}	160
U^{235}O_2	175
Power density, Mw/ ℓ	
Average	0.76
Maximum	1.14
Minimum	0.57
Diameter, cm	43.3
Height, cm	43.3
Volumetric distribution, %	
Fuel	
Axially	62.5
Radially	62.5
Overall	40
Coolant, overall	40
Ratio between inlet and outlet headers	1:2
Structure, overall	20

Fuel Assemblies (See Figs. 1 and 2)

Shape	Hexagonal
Distance between flats, cm	6.35
Number (layers) of fuel elements/assembly	18
Thickness of fuel in bed, cm	1.27
Particle size of fuel, microns	200
Bed porosity	0.4
Surface area of beds/layer, cm^2	893
Surface area of beds, total cm^2	16,275

Table 7 (Cont'd.)

<u>Coolant</u>		
Inlet pressure		
kg/cm ²		41.3
atm		40
Flow rate, kg/sec		
Total flow		11.4
Average/layer		0.64
Mass flow rate, g/(cm ²)(sec)		
Per layer, average		0.71
Per bed		
Maximum		1.1
Minimum		0.28
Maximum Δp , kg/cm ²		
Loss in beds		0.7
Loss in primary system (less beds)		0.35
Total Δp loss in primary system, kg/cm ²		1.05
<u>Temperature, °C</u>		
Inlet		150
Outlet		980
Δt_m		55
<u>Gas Velocity in Vertical Headers (Maximum), m/sec</u>		
Inlet		76
Exit		99
<u>Fuel</u>		
Volume in core, ℓ		26.4
Power density of the fuel, Q, Mw/ ℓ		
Average		2.50
Maximum		3.75
Minimum		1.86
Pump power requirements		
Fractional pumping power ratio, w/QL		
Bed		0.015
Primary system		0.008
Ratio of pumping power to total power generated, primary system, %		7.5

C. UC-H₂ Reactor Concept

A conceptual fast reactor system was designed to use hydrogen for coolant, uranium monocarbide for fuel, and hydrogen-resistant metallic carbides for structure, including porous carbides to support the fuel beds. The geometry shown in Fig. 2 was used, except that the blanket was replaced by a reflector. Based upon estimates by Loewenstein, the critical mass will be 200 kg of U²³⁵ (220 kg UC, 200-micron-sized particles) and the core volume will be 95ℓ. The core volume will provide space for the carbide structure in the system, and for the increased gas volumes due to the higher temperature rise (93 to 2320°C) in the coolant. The inlet gas pressure was set at 60 atm (63 kg/cm²). A pressure drop of 5.25 kg/cm² in the fuel bed (2.54 cm thick) was calculated, and a pressure drop of 1.75 kg/cm² was assumed for the balance of the primary system, resulting in an exit pressure of 56 kg/cm² from the reactor system. The power output of the core was calculated to be 240 Mw, with an average core density of 2.5 Mw/ℓ.

Since experimental data are not available for this system, the pressure drop calculations were based upon the curves shown in Ref. 12 for fluid flow in packed beds. The mass flow rates for constant exit temperature were calculated to vary from 0.38 to 0.75 g/(cm²)(sec) of coolant. Using the mass transfer equation (j_h) for calculating heat transfer values, an average value of h was found to be 2.9 w/(cm²)(°C). Assuming a mean temperature difference between gas and solid of 80°C, the power density of 11 Mw/ℓ of fuel included a safety margin of four.

For higher performance, using mass flow rates of 2 g/(cm²)(sec), and for the same initial gas temperature and an outlet temperature of 2200°C, a fuel particle size of 100-micron diameter and a mean temperature difference of 120°C gave an average value for h of 4.6 w/(cm²)(°C) and a power density of 200 Mw/ℓ of fuel. If a safety factor of 4 is applied to allow for inhomogeneous coolant flow and particle characteristics, then a power density of 50 Mw/ℓ of fuel can be assumed for this system. The application of carbon coatings to the fuel should prevent sintering, since the carbon will sublime rather than melt or soften. Thus, if the maximum permissible carbon temperature is 3000°C, it should be possible to achieve gas temperatures higher than 2320°C if higher melting fuels are used.

Table 8 shows the design data for the 95-liter core. A maximum to average ratio of power density of 1.5 and a maximum to minimum ratio of power density of 2 was assumed, along with constant gas exit temperature.

Table 8

UC-H₂ REACTOR CONCEPT DATACore

Power output, Mw	240
Volume, ℓ	95
Critical mass, kg	
U ²³⁵	200
U ²³⁵ C	220
Volume ($\bar{X} = 0.4$), ℓ	33
Power density, Mw/ ℓ	
Average	2.5
Maximum	3.75
Minimum	1.87
Diameter, cm	50.3
Height, cm	50.3
Cross sectional area, cm ²	1980
Volumetric Distribution, %	
Fuel	
Radial	70
Axial	50
Overall	35
Coolant	
Radial	20
Axial	25
Overall	35
Structure	
Radial	10
Axial	25
Overall	30

Fuel Assemblies (See Figs. 1 and 2)

Structural material (H ₂ resistant)	carbides/carbon/graphite
Shape of assembly	Hexagonal
Distance between flats, cm	7.62
Number of elements/assembly (layers in core)	10
Number of assemblies	37
D _p , particle size, microns	200
Area density, cm ² /cm ³	$\sim 1.8 \times 10^2$

Table 8 (Cont'd.)

Axial thickness/bed, cm	
Fuel	2.54
Coolant	1.27
Structure (includes porous bed support)	1.27
<u>Coolant</u>	
Flow rate, kg/sec	
Total	7
Per layer average	0.7
Mass flow rate, g/(cm ²)(sec)	
Average	0.5
Maximum	0.75
Minimum	0.38
Gas velocities - superficial (maximum), cm/sec	
Inlet	192
Outlet	1525
Velocity, m/sec	
Inlet header	
Maximum	366
Average	183
Outlet header	
Maximum	366
Average	183
<u>Temperatures, °C</u>	
Inlet	93
Outlet	2320
Δt	80
<u>Pressure, kg/cm²</u>	
Inlet	63
Outlet	56
Δp across bed	5.25
Δp , balance of reactor pressure losses	1.75
<u>Fuel</u>	
Power density, Mw/ ℓ	
Maximum	11
Average	7.56
Minimum	5.5
Fractional pumping power η , w/Q	<0.024

VI. CONCLUSIONS

This preliminary study reflects some possible applications and performance characteristics of the convection-cooled, packed-bed fuel element to high-temperature and high-power density reactors.

This study was limited to the use of helium-cooled beds. Curves for evaluating the effect of particle size bed thickness and porosity on bed performance with various coolant flow rates are included.

Although the study was primarily limited to relatively modest values of temperatures and power density, it is clear that the basic features of the packed-bed fuel element lend themselves to operation at substantially higher performance. The report also contains an example of a H_2 -cooled, UC-fueled bed which is shown capable of operating at much higher temperatures and power densities.

In general, it appears that reliable data required for the engineering design of packed-bed fuel elements, especially with respect to fluid flow and irradiation, must be determined experimentally.

Listed below are the specific conclusions resulting from this study:

1. The power density in a fuel bed varied with the mass flow rate of coolant and specific heat of the coolant, and varied inversely with the fuel particle size. For the size of particles used, the power density was not particularly affected by thermal conductivity of the particle material or thermal stress in the particle.
2. Temperature of the effluent gas varied inversely with the mass flow rate of coolant and directly with the maximum permissible fuel surface temperature. The fuel temperature was limited by the sintering characteristics of the fuel for long-term operation, and the melting, softening point, or sublimation temperature of the fuel for short-term operation.
3. Pumping efficiency varied directly with the system pressure, particle size, porosity of the bed, and temperature rise of the coolant, and varied inversely with the bed thickness.
4. Data on the effects of radiation damage to the individual particles in a packed bed or on the performance of the bed could not be determined from information in the literature, but it is expected that any effect will be small.

5. Reasonably accurate values for area densities can theoretically be calculated for clean uniform beds. The effects of variation in sizes, shapes and surfaces of particles, and contact areas between particles for various arrangements indicate that these values must be determined experimentally.

6. Confidence in values of heat transfer coefficients for use in particle beds of interest determined by present solutions is not justifiable. Reasonably reliable values should be determined experimentally.

7. Provisions for metering flow to individual beds will be required to provide desired cooling rates, although preferential and limited deposition of entrained solids in the gas bed may provide a natural orificing system. Retention of particles in the bed can be achieved.

8. The use of inert coatings on particles may provide means for improving corrosion resistance, deterring sintering and spallation, and limiting fission product release from the particles.

9. Stable bed porosities from 0.38 to 0.42 can be achieved by normal handling methods. Studies indicate that stable bed porosities up to 0.86 can be achieved by arching and bridging the spherical particles. Practical methods for achieving the high porosities have not been developed. The use of irregularly shaped particles may provide a method of achieving higher bed porosities.

10. The presence of contaminants in the coolant, such as H_2O and O_2 , may seriously affect the corrosion rates of the fuel and structure. Identification and control of the corrosion mechanism will be necessary for extended bed operation.

11. Stability of flow through the bed is enhanced by minimizing pressure drop through the bed.

VII. RECOMMENDATIONS

The order of the recommendations are based upon the assumption that capability of the fuel should be demonstrated experimentally to a satisfactory degree before undertaking detailed engineering and design of reactor systems and components to use this fuel element concept. It is obvious, of course, that fuel development cannot proceed completely independently of the other phases, and the amount of concurrent effort on the other design phases will depend upon the urgency of the project and the availability of funds and manpower.

A recommended program to be followed is described herewith:

1. Expand the present experimental study to include materials and coolants other than UO_2 and helium, and develop methods for preparing fuel particles and particle beds to provide optimum performance. The work should also cover development of new materials, where indicated.
2. Undertake fluid flow studies which approach realistic conditions of pressure and temperature, and develop reliable calculating methods for systems of interest, as well as determining the critical parameters of fuel-bed design.
3. Perform out-of-pile measurements on heat transfer coefficients in packed beds, and develop reliable calculating methods for systems of interest.
4. Undertake a series of in-pile functional tests to confirm and to demonstrate the feasibility of the packed-bed fuel element, and confirm insofar as is possible any changes in heat transfer and fluid flow due to radiation.
5. Undertake preliminary worthwhile conceptual reactor designs which are amenable to the packed-bed fuel element based on data generated by the experimental program.
6. Undertake detailed design and development of fuel elements and assemblies and other critical components for the more promising reactor concepts.
7. Based upon favorable progress on problems noted above, undertake the detailed design, construction, and operation of a reactor experiment that will demonstrate the utility of the packed-bed fuel element for a particularly promising application.

NOMENCLATURE

A	Area density
A_1	Area of bed
κ	RT_0/M
χ	R/Mc_p
c_p	Specific heat (constant pressure)
C	Correction factor
$^{\circ}\text{C}$	Degrees Centigrade
D_p	Diameter of particle
D_c	Diameter of capillary tube
E	Young's modulus
e	Poisson's ratio
f	Friction factor
F	Fractional escape of nuclides
ΔF	Free energy of formation
G	Mass flow rate
g_c	Gravitational constant
h	Heat transfer film coefficient
$^{\circ}\text{K}$	Degrees Kelvin
k	A constant
k_t	Thermal conductivity of gas
L	Depth of bed
M	Molecular weight of gas
η	Fractional pumping power
P	Permeability coefficient
p	Pressure
Δp	Pressure difference
p_1	Initial pressure
p_2	Exit pressure
$(d\ell)\bar{w}_f$	Pressure loss due to friction
α	Empirical constant used to correct for change in viscosity with temperature

β	Empirical constant used to correct for change in viscosity with temperature
ϕ	Coefficient of expansion
σ	Thermal stress
λ	Decay constant
ϵ_0	Creep rate
ρ	Density
μ	Viscosity
a	$\alpha\kappa/g_c$
b	$\beta\kappa/2g_c$
m	$\alpha\chi/2g_c$
n	$\beta\chi/3g_c$
r	Radius of particle
R	Universal gas constant
$^{\circ}R$	Degrees Rankine
Q	Volumetric heat generation rate
Re	Reynolds Number
Re'	Modified Reynolds number
St	Stanton number
Pr	Prandtl number
j_h	Mass transfer function
T	Absolute temperature
T_0	Absolute inlet temperature
Δt	Temperature difference
$\bar{\Delta} t_m$	Mean temperature difference
t_1	Inlet temperature
t_2	Outlet temperature
t_g	Temperature of gas
t_s	Temperature of solid
t_{av}	Average temperature
v	velocity - when used with packed beds indicates superficial velocity; (velocity of gas in tube approaching/leaving the bed).

V	volume
w	work of pumping
W	mass
x	Fractional depth of bed
$\bar{X}$	Porosity of bed
Z	Activation energy for creep process
ψ	Particle sphericity

REFERENCES

1. W. A. Lambertson and M. A. Mueller, Uranium Oxide Equilibrium Systems, J. Am. Ceramics Soc. 36, 329-334, 365-368, 397-399 (1953).
2. Pyrographite, Raytheon Company High Temperature Materials Department, Waltham, Massachusetts.
3. International Symposium on High Temperature Technology, Stanford Research Institute, Palo Alto, California (1959).
4. L. Groton and H. Fraser, Systematic Packing of Spheres, J. of Geology 43, No. 8, Pt. 1, 785-909 (November-December 1935).
5. J. Hrubicek, Filtration Geometry of Spherical Systems, Kolloid Bechefti 5, 385 (1941).
6. E. J. Seldin and S. Mrozowski, Permeabilities of Baked Carbons and Beds of Carbon Powders to the Flow of a Gas, Proceedings of 1957 Conference on Carbon, pp. 687-703, Pergamon Press.
7. H. Kittel, ANL (Private Communication).
8. R. J. Ackermann, et al., Free Energies of Formation of Gaseous Uranium, Molybdenum and Tungsten Oxides, J. Phys. Chem. 64, 350 (1960).
9. J. A. Lane and Ad Hoc Study Group, A Study of Problems Associated with Release of Fission Products from Ceramic Fuels in Gas-Cooled Reactors, ORNL-2851 (1959).
10. B. M. Abraham and H. E. Flotow, UO₂-NaK Slurry Studies, Nuc. Sci. & Engr. 2, 501 (1957).
11. J. M. Dalla Valle, Micrometrics, Pitman Publishing Company (1948).
12. G. G. Brown and Associates, Unit Operations, Wiley and Sons, New York (1950).
13. A. E. Scheidegger, The Physics of Flow Through Porous Media, MacMillan Company, New York (1957).
14. L. E. Brownell and D. L. Katz, Flow of Fluids through Porous Media, Chemical Engineering Program, 43, No. 10, 537-548 (1947).
15. E. B. Baumeister and A. O. Bennett, Fluid Particle Heat Transfer in Packed Beds, AIChE Journal 4, No. 1, 69-74 (March, 1958).

16. L. Green, Jr., Gas Cooling of a Porous Heat Source, J. Applied Mechanics 19, 173-178 (1952).
17. R. W. Bussard and A. D. Delauer, Nuclear Rocket Propulsion, McGraw-Hill Book Co., New York (1959).