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PARTICLE FUEL BED TESTS*

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ABSTRACT

Gas-cooled reactors, using packed beds of small diameter coated fuel particles have been proposed for compact, high-power systems. The particulate fuel used in the tests was 800 microns in diameter, consisting of a thoria kernel coated with 200 microns of pyrocarbon. Typically, the bed of fuel particles was contained in a ceramic cylinder with porous metallic frits at each end. A dc voltage was applied to the metallic frits and the resulting electric current heated the bed. Heat was removed by passing coolant (helium or hydrogen) through the bed.

Candidate frit materials, rhenium, nickel, zirconium carbide, and zirconium oxide were unaffected, while tungsten and tungsten-rhenium lost weight and strength. Zirconium-carbide particles were tested at 2000 K in H_2 for 12 hours with no visible reaction or weight loss.

INTRODUCTION

Gas-cooled reactors using packed beds of small diameter coated fuel particles have been proposed for compact, high-power systems (1). Tests have been conducted on packed beds of HTGR-type fuel particles to determine power density capability, response to rapid temperature ramps, and compatibility with coolant and candidate frit materials. The particulate fuel used was 800 microns in diameter, consisting of a thoria kernel coated with 200 microns of pyrocarbon (see Figure 1). This fuel was produced by GA Technologies Inc., as was a similar fuel with an outside coating of zirconium carbide to resist hydrogen gas (2). Typically, the bed of fuel particles was contained in a ceramic cylinder with porous metallic frits at each end. The bed was brought to power by resistive heating of the pyrocarbon coated particles to simulate nuclear

heating. A dc voltage was applied between the metallic frits and the resulting electric current through the particles heated the bed. Heat was removed by passing coolant (helium or hydrogen) through the bed. Operating temperatures up to 2000 K were investigated.

METHODS

The specific resistance was measured during numerous tests of the bed at various temperatures and the results are plotted in Figure 2. The resistance was calculated from the recorded amperage through the bed and the voltage read between two probes located in the bed one cm apart. The bed area was used to calculate amperage per square centimeter.

$$\rho = \frac{V \cdot A}{I}$$

where ρ = specific resistance

V = voltage drop per cm

A = total bed cross sectional area at probes, cm^2

I = total amperage thru bed

The temperature of the bed was measured by a disappearing filament optical pyrometer through the quartz tube wall in some cases and in others a thermocouple midway between the probes recorded temperature. There was general agreement between the two methods.

The results of more than two dozen experiments indicated the specific resistance of the bed containing 800 micron pyrocarbon-coated particles was 0.09 ± 0.02 ohm-cm at 1273 K. At 1600 K the observed specific resistance was 0.06 ohm-cm in a transient cross experiment.

A 20-mm diameter quartz tube 30-cm long was used to hold a bed of the

pyrocarbon spheres between two porous stainless steel frits. The bed freight was 2.5 cm and the lower end of the tube was attached to a helium supply pipe. The upper frit was spring loaded with a force of seven pounds. Each of the frits had six nickel wires welded to its surface. The wires were brought out and connected to a power supply.

Voltage was applied to the bed to heat it and helium was forced through the bed to keep the temperature at 1273 K. Typical readings were 12 volts, 60 amperes, 10 psi helium, bed temperature 1323 K (optical rdg.), helium outlet 1208 K (thermocouple). T power density with this arrangement was limited to 300 watts per cm^3, because the frits were temperature limited.

To obtain higher power densities, a cross arrangement was designed where the power was applied at a right angle to the flowing helium. Solid nickel electrodes which were air cooled carried the current to the bed, while the helium flowed through the bed and frits.

The pressure drop through the packed bed correlated quite well with Ergun's equation (3)

$$\Delta P = \left(\frac{150 \cdot XSFO}{Re} + 1.75\right) \frac{\Delta \cdot G^2 \cdot XSFO}{\rho \cdot D_p \cdot \varepsilon^3 g_c}$$

where ΔP - pressure drop

XSFO - packing fraction of bed

$\varepsilon = (1 - XSFO)$ - free volume fraction

Δ - height of bed

G - specific mass flow of gas

ρ - gas density

D_p - diameter of particles

μ - viscosity of gas

g_{dc} - gravitational constant

$Re = D_p G/\mu$

The conditions of this experiment were:

Bed material - 800 μm pyrocarbon coated spheres

Bed density - 1.83 gms/cc

Bed size - 2 cm^3 cube

He flow - 1.5 liter/sec STP

Bed temperature - 1273-1473 K

He inlet temperature - room temperature

He outlet temperature - 1073 K

He inlet press - 18 psig

He outlet press - 0 psig

Inlet frit - coarse quartz

Outlet frit - slots in ss. disc

Initial power input - 300 watts

Final power input - 1200 watts

Calculated from Ergun's equation:

$$\Delta P_{calc} = 20 \text{ psi}$$

The experiments included a series of fast ramp tests to operating temperature (with rise times down to as little as three seconds) as well as long steady power level tests lasting several hours. Upon completion of each test, the fuel and frits were removed for evaluation. The fuel particles were unaffected and retained coating integrity. The frit materials showed virtually no reaction except where local temperatures occasionally exceeded the melting point. As one example of the experiments, Table 1 shows results for a

transient approach to steady-state conditions in a cross type packed bed. At final operating conditions, the temperature difference between the bed particles and helium is 54 K, indicating an overall heat transfer of 0.3 W/cm^2-K, which agrees with theory (4).

$$Nu = [(1.18\ Re^{0.58})^4 + (0.23\ Re^{0.75})^4]^{0.25}$$

$$Nu = \frac{hD}{k} \qquad Re = \frac{DG}{\mu}$$

where h = heat transfer coefficient of gas film

D = spherical diameter of bed particles

G = superficial mass flow of gas through bed

k = thermal conductivity of gas

μ = viscosity of gas

A number of packed bed configurations were investigated, including cylindrical beds with end frits, annular beds between concentric frits, and cubic beds with 4-way cross openings. The cross experiments allowed the use of ceramic frits which also were tested. Most tests were carried out at approximately 1 atm coolant pressure; in some cases, a pressure tight enclosure was used which allowed operation of the bed at 11 atms. Typical results from this series of experiments are shown in Table 2. Pressure drops through the beds were on the order of 1 atm. Pressure drops and temperature gradients were measured in all experiments. For those tests carried out at 1 atm pressure, gas outlet temperature was about 100 K below the maximum bed temperature. The cross tests allowed fast temperature ramp tests to 1800 K. For long operation, maximum temperature was kept at about 1500 K. Bed power densities up to ≈1500 W/cm^3 were investigated.

MATERIALS TESTS

In a series of experiments on compatibility, candidate frit materials were exposed in a high temperature furnace at temperatures of ≈1500 and ≈2000 K in both helium and hydrogen for extended periods (i.e., 12 hours for H_2 and 150 hours for He). Rhenium, nickel (1500 K only), zirconium carbide, and zirconium oxide were unaffected, while tungsten and tungsten-rhenium lost weight and strength. Zirconium carbide particles of approximately the same outer diameter as ZrC-coated fuel particles were tested at 2000 K in H_2 for 12 hours. They showed no visible reaction or weight loss (Table 3).

DISCUSSION

The results of these tests indicate the use of particle fuel is feasible at power densities of at least 1500 MW/m^3 using He or H_2 gas coolants. Both rhenium and zirconium carbide were found to be suitable porous frit materials for maintaining the bed configuration and allow passage of the gas at temperatures of ≈2000 K.

Tungsten and tungsten-rhenium wire were found to be unsuitable for long term use in helium because of extensive weight loss. This was probably due to reaction with impurities in the helium, possibly the classic water vapor cycle.

Tungsten and tungsten rhenium retained the weight in H_2 coolant, but became brittle when tested at room temperature because of recrystallization at the high temperatures. If these materials could be maintained and used without falling below the ductile to brittle transition temperature (≈573 K), they could be potential candidates for the hot frit.

CONCLUSIONS

Material and thermal hydraulics for compact reactors of less than a cubic meter with a high power density and direct gas cooling of the particulate fuel have been experimentally investigated. The preliminary results indicate that such systems are practical.

ACKNOWLEDGEMENT

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FIGURE CAPTIONS

1. Cross sections of types of coated fuel particles; top - low burnup, bottom - high burnup

2. Specific electrical resistance of beds of pyrocarbon-coated spheres; 800 micron diameter with 200 micron coating

TABLE I

Transient Cross Experiment (Typical)

12x12 mm diam bed

800 μm pyrocarbon-coated spheres of ThO_2

Quartz frits, vent to atmosphere

Electrodes at right angle to He flow

He Flow liters/min	He Exit Temperature °C	He Inlet Pressure psig
103 (Start)	120	6.8
98.0	249	7.8
93.5	448	9.0
84.5	703	10.5
80.0 (Finish)	866 (bed 920°C)	11.5

Applied voltage, 11.56; amperage, 90; input wattage, 1040

Output heat in H_2, 977 watts (conditions at end of experiment).

TABLE 2

Typical Pressurized Bed Experiment

Bed - 800 μm spheres

Bed Volume - 3.5 cm^3

Helium Flow - 800 liters/min

He Inlet Pressure - 164 psig

He Outlet Pressure - 157 psig

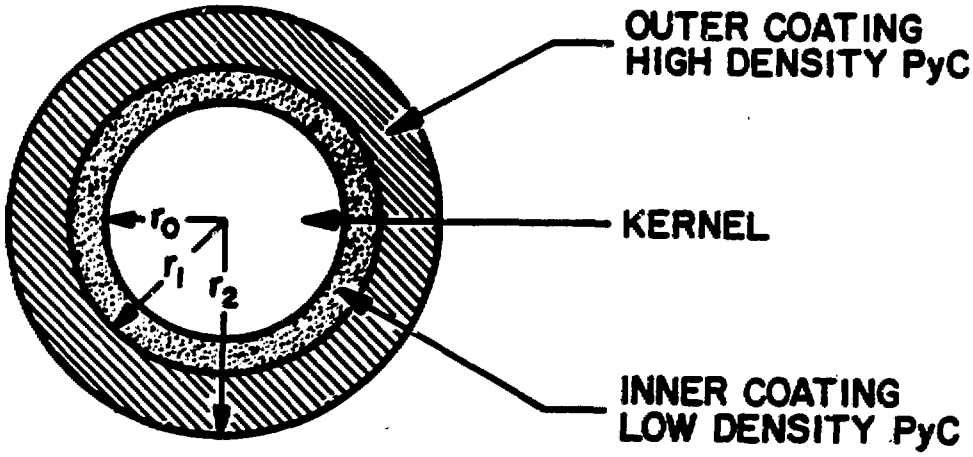
He Outlet Temperature - 856°C

Distance Along Bed	He Temperature
Inlet	22°C
1 cm	150
2	525
3	600
4	815
Outlet	865

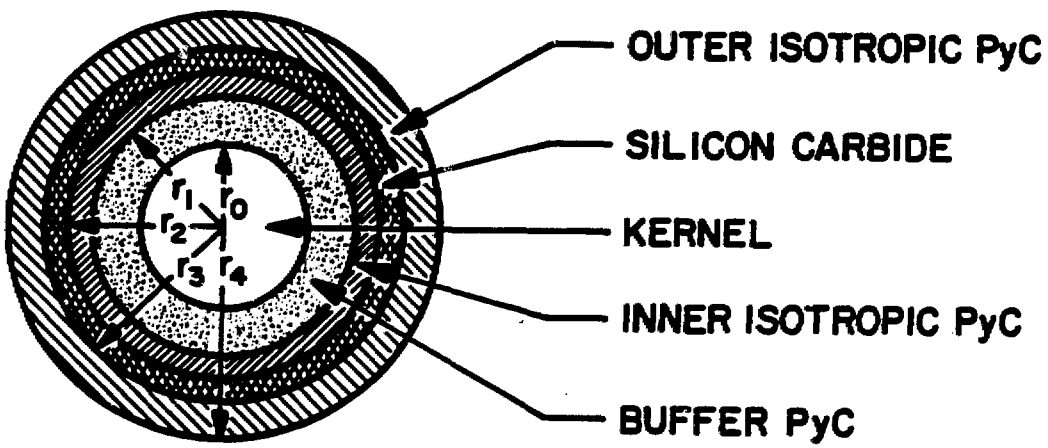
TABLE 3

Static Tests of Frit Materials

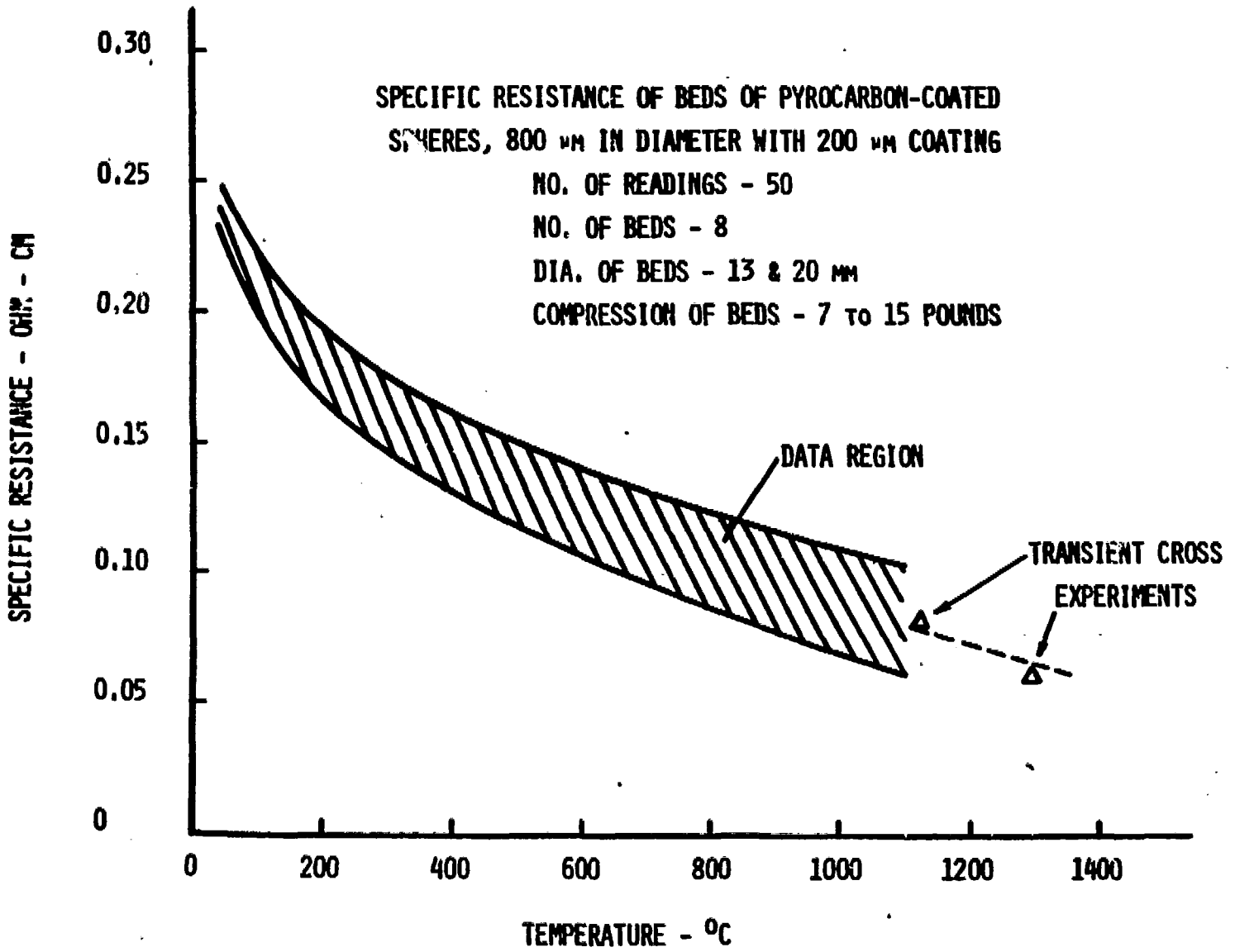
Material	Average Temperature °C	Time hours	Gas	Results
Re-foil	1200	144	He	No change (<0.1%)
W-wire	1200	144	He	Lost 35% of wt.
W-Re-wire	1200	144	He	Turned to powder
Re	1700	4	He	No change (<0.1%)
W	1700	4	He	Lost 21% of wt.
W-Re	1700	4	He	Lost 36% of wt.
Re	1700	4	H_2	No change (<0.1%)
W	1700	4	H_2	Brittle
W-Re	1700	4	H_2	Lost 50% of tensile strength
ZrC pieces	1700	4	H_2	No change (<0.1%)
ZrO_2 insulation	1700	4	H_2	No change (<0.1%)
ZrC with W-Re wire	1700	4	H_2	No change (<0.1%)


OUTER COATING
HIGH DENSITY PyC
KERNEL
INNER COATING
LOW DENSITY PyC
r_0
r_1
r_2

(a)


OUTER ISOTROPIC PyC
SILICON CARBIDE
KERNEL
INNER ISOTROPIC PyC
BUFFER PyC
r_1
r_0
r_2
r_3
r_4

(b)


SPECIFIC RESISTANCE OF BEDS OF PYROCARBON-COATED SPHERES, 800 µm IN DIAMETER WITH 200 µm COATING
NO. OF READINGS - 50
NO. OF BEDS - 8
DIA. OF BEDS - 13 & 20 mm
COMPRESSION OF BEDS - 7 to 15 POUNDS
DATA REGION
TRANSIENT CROSS EXPERIMENTS
SPECIFIC RESISTANCE - OHM. - CM
0.30
0.25
0.20
0.15
0.10
0.05
0
0
200
400
600
800
1000
1200
1400
TEMPERATURE - °C