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THE APPLICATION OF GAS-CERAMIC
MIXTURES TO NUCLEAR POWER

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OAK RIDGE SCHOOL OF REACTOR TECHNOLOGY

F. C. VonderLage, Director

THE APPLICATION OF GAS-CERAMIC MIXTURES TO NUCLEAR POWER

D. C. Schluderberg

August 1955

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PREFACE

In September, 1954, the author embarked on the twelve months of study which culminated in this report. For nine of these months, formal classroom and student laboratory work occupied his time. At the end of that period, the author was presented with a problem in reactor design.

This is a summary report of the study, the research, the problems, and the solutions which developed during the final ten-weeks period of the school term. It must be realized that, in so short a time, a study of this scope can not be guaranteed complete or free of error. This "thesis" is not offered as a polished engineering report but rather as a record of the work done by the student under the leadership of his advisor. It is reproduced for use by those persons competent to assess the uncertainties inherent in the results obtained in terms of the preciseness of the technical data and analytical methods employed in the study. In the opinion of the students and faculty of ORSORT, the problem has served the pedagogical purpose for which it was intended.

As a matter of historical fact and pride we point out that similar investigations by students of previous ORSORT classes have led to sufficiently encouraging results to warrant more exhaustive studies; in at least one instance a reactor first investigated by a student group is soon to become a physical reality. There is also recorded an instance in which calculations contained in a similar report were uncritically abstracted and applied to a study for which they were never intended. It is to avoid the recurrence of the latter experience that we have taken some pains to acquaint the reader with the character of this report.

The faculty wishes to join the author in an expression of appreciation for the assistance which various members of the Oak Ridge National Laboratory have so generously contributed. In particular, the guidance of the advisor, Dr. J. M. Warde, is gratefully acknowledged.

F. C. VonderLage

for

The Faculty of ORSORT

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ACKNOWLEDGEMENTS

The author wishes to express his appreciation for the opportunity to work on this subject here at the Ceramics Laboratory in Y-12.

The cooperation, encouragement and help of the following individuals is also gratefully acknowledged:

L. G. Alexander
J. H. Frye
J. R. Johnson
F. C. VonderLage
J. M. Warde

This work was made possible through the efforts of Drs. Frye, VonderLage and Warde. Dr. Warde also provided laboratory facilities, test equipment and, along with Dr. Johnson, gave the author a great deal of encouragement and inspiration. Invaluable technical counsel was afforded the author by Drs. Alexander and Johnson. Helpful suggestions were also offered by S. T. Robinson and R. Bennenati of Sanderson and Porter.

The author also wishes to mention that the services of laboratory personnel, millwrights, pipe fitters, and electricians were of high quality and that the administration of these services was very effective. This made it possible to assemble the rather elaborate test apparatus used in a matter of weeks.

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ABSTRACT

Gas-ceramic mixtures appear to be ideally suited for use as reactor coolants and thermodynamic media in a closed cycle gas turbine type of nuclear power plant. With better coolant, thermodynamic, and nuclear properties than gases, and possessing unique system decontamination properties; these mixtures greatly improve the competitive position of this type of plant in relation to other types using liquids and vapors as reactor coolants and thermodynamic media respectively.

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THE APPLICATION OF GAS-CERAMIC MIXTURES TO NUCLEAR POWER

Introduction

Many of the underlying difficulties encountered in the design of power reactors arise from the shortcomings of the available liquid, gas, or vapor coolants which must receive the reactor heat.

Liquids, though ideal as heat transfer fluids, are by their very nature unsuited for use at attractive power reactor temperatures. Their use always brings attendant problems such as: corrosion; high vapor pressure; solidification at room temperature; undesirable chemical characteristics; the need to transfer heat to gas or steam through a heat exchanger or boiler; and so on.

On the other hand, gases and vapors are characteristically well suited for high temperature applications but possess lower heat capacity per unit volume and produce lower rates of heat transfer, both of which increase the difficulty of extracting heat from power reactors.

These shortcomings of gases may be overcome by the addition of a finely divided refractory powder, such as graphite, held suspended in the gas by flow turbulence.

The desirable properties to be expected of gas-ceramic mixtures may be summarized as follows:

1. Better coolant characteristics than a gas.
2. Better thermodynamic properties than a gas.
3. Better nuclear properties than a gas.
4. Possible system decontamination properties.

The purpose of this project is to investigate these properties to the fullest extent possible in the time available with particular reference to numbers 1, 2 and 4.

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The fullest utilization of these properties appears to be in a nuclear power plant of the type shown in Figure 1. Except for the reactor coolant bypass* and the solids concentrator to increase the ceramic powder loading in the mixture cooling the reactor, the arrangement is similar to Figure 2 which is the usual plant arrangement for a closed cycle gas turbine system and a gas cooled reactor. The concentrator and reactor bypass are used for the following reasons:

1. Reactor can be run at higher temperatures than maximum operating temperature of turbo-machinery.
2. Concentration of ceramic powder to obtain optimum thermodynamic conditions in turbine and compressor is not high enough to get optimum reactor cooling and nuclear properties. The concentrator remedies this by increasing the loading of that part of the mixture sent through the reactor at the expense of loading in the bypassed flow.
3. Assuming the concentrated mixture flowing through the reactor has a significant moderating effect, variation of the concentration may be a convenient means of reactor control.
4. Assuming the reactor has a negative temperature coefficient, power output of the system could be easily controlled by means of a second bypass (not shown in Fig. 1) which would bypass concentrated mixture around the reactor.

Of course the gas-ceramic mixture could be used in the arrangement shown in Figure 2 at the expense of the advantages listed above. The gas-ceramic mixture is not only used to cool the reactor but also is the thermodynamic medium which does work in the turbine, is cooled in the regenerator and cooler, compressed in the compressor and heated in the regenerator.

* The reactor coolant bypass is due to J. R. Johnson, ORNL Ceramic Laboratory.

This type of plant shows promise of being more economical, more efficient, more compact, easier to maintain and easier to control than a similar plant using gas alone as a reactor coolant and thermodynamic medium. It should also be competitive with other type nuclear power plants using liquids and vapors as reactor coolants and thermodynamic media respectively.

Coolant Characteristics

a. Heat Capacity

Low heat capacity is probably the greatest shortcoming of gaseous reactor coolants. This difficulty is completely overcome by the addition of ceramic powder to a given gas. To illustrate this, the heat capacity (Btu absorbed in reactor/ft³ coolant leaving reactor) of gas-ceramic mixtures under various conditions; and of sodium, pressurized water, N₂ and CO₂ under typical conditions are tabulated below. All gas-ceramic mixtures are considered to be at 1500 psia with a conservative loading of 10 lb. graphite/lb. suspending gas. Actually, loadings as high as 15 or more may be feasible.

<u>Coolant</u>	<u>Temp. Rise</u>	<u>Outlet Temp.</u>	<u>BTU Absorbed per ft³ Coolant Lv. Reactor</u>
1. Pressurized H ₂ O	35	500	1900
2. Sodium	400	1000	7140
3. N ₂ -Graphite, No. Regen.	900	1300	7770
4. N ₂ -Graphite, Regen.	300	1300	2582
5. N ₂ -Graphite, High Temp. Reactor (Ceramic Elements)	2000	3000	10400
6. CO ₂ -Graphite, No Regen.	900	1300	11070
7. CO ₂ -Graphite, Regen.	300	1300	3710
8. N ₂ -No Regen.	500	1300	301
9. CO ₂ -No Regen.	500	1300	494

It is believed that with the heat capacities shown above, gas-ceramic mixtures will be ideal reactor coolants even if heat transfer rates do not increase sufficiently over that of gases alone to be comparable to liquid coolants. This is because:

1. Extended surface can be utilized to increase heat transfer.
2. A larger temperature difference is available for reactor cooling due to absence of intermediate heat exchanger.
3. There will be no corrosion products to add thermal resistance.

b. Heat Transfer

Since there was no information available on this or how such mixtures acted when flowing through pipes, heat exchangers, compressors, nozzles, etc., it was necessary to hastily build the test loop shown in Figure 3.

This loop has two six stage blowers connected in tandem. The combined pressure rise to both blowers is used to pass the mixture through a flow nozzle and then a heat exchanger which removes heat put into the loop by the blowers. The heat exchanger was put at a 45° angle to give good self cleaning characteristics. The flow nozzle was made of 2S aluminum so that any erosive tendency of the suspended ceramic would be easily noticed. A tank with a filter bag installed inside was installed in a bypass so that the system could be cleared of ceramic powder when desired. Practically all of this equipment was obtained from salvage. It is limited to pressures below 25 psia and temperatures not exceedingly 250 °F. Within these limits it is proving useful for obtaining heat transfer, pressure drop, and flow nozzle data and for showing feasibility of the general idea.

Only a limited amount of heat transfer data for N₂ and graphite mixtures is available at the time of this report.

The curve on Figure 4 shows how the addition of graphite increased heat transfer rates in the heat exchanger. The ordinate is the ratio of test

heat transfer rate between mixture and heat exchanger tube surface to the calculated value for N_2 alone at the same velocity using the Colburn equation. The method for computing graphite loading is described in the Appendix.

Figure 5 shows how heat transfer rate and mixture velocity in the heat exchanger tubes vary with graphite loading for a given mixture pressure drop in the heat exchanger. This shows a gradual increase in heat exchange for a given pressure drop as graphite is added.

Figure 6 shows the relation of heat transfer rate to mixture heat capacity which is defined as:

$$W_g C_g + W_s C_s$$

Where

W_g = Flow rate of N_2 (lb/hr)

C_g = Specific heat of N_2 at constant pressure (Btu/lb°F)

W_s = Flow rate of suspended solid (lb/hr)

C_s = Specific heat of suspended solid (Btu/lb°F)

Additional heat transfer data will be obtained for N_2 and graphite up to loadings of about 3.0 lb graphite/lb N_2 to be followed by mixtures of CO_2 and graphite, and activated carbon in N_2 and CO_2 .

There is not enough power available in the test apparatus to go to loadings above about 3.0 lb/lb N_2 . Actually much higher loadings seem possible since work by Gasterstadt on the air conveyance of wheat in horizontal pipes shows loadings up to 14 lb/lb of air at a velocity of 53 ft/sec.

Thermodynamic Properties

These are markedly different from those of a gas due to the strong thermal bond which exists between fine particles and a suspending gas. This is due to the large surface area of the particles and the high rate of heat transfer between gas and particles. For instance, 2 micron graphite particles suspended

in CO_2 have about $13,000 \text{ ft}^2$ of surface per pound and a heat transfer rate to the gas of about $12,000 \text{ BTU/Hr}^\circ\text{F ft}^2$. Thus a degree of temperature difference between a pound of graphite and CO_2 will cause heat to flow between the two at a rate in the order of 156 million BTU/hr.

The result is that when a mixture is rapidly cooled as it flows through a nozzle, the gas and suspended particles will remain at nearly the same temperature. For example, in a mixture of air and graphite flowing at 1000 ft/sec and cooling 100° F in 1-1/2" of travel, the graphite will only be 7.0° F hotter than the air.

Figure 7 shows the effects these properties have on an ideal power cycle. Here on a temperature entropy diagram is a representation of the states of a thermodynamic medium in all parts of a closed cycle gas turbine system. In the turbine, heat in the form of work is extracted from the gas by adiabatic expansion from a high pressure to a low pressure. Similarly, the compressor does work on the gas in compressing it adiabatically from a low to a high pressure. If the plant has a regenerative heat exchanger, the turbine exhaust can be theoretically cooled to compressor outlet temperature by exchanging its heat to gas leaving the compressor, which is thereby heated to turbine exhaust temperature. Heating from regenerator outlet temperature to turbine inlet temperature is accomplished in the reactor and cooling from regenerator outlet temperature to compressor inlet temperature by cooling water, or air, in another heat exchanger.

The shaded area represents the net work output of the cycle per pound of gas with no ceramic powder added.

As a ceramic powder is added to the gas, the paths through the turbine and compressor change as shown by the dotted lines. Notice that the area of the cycle increases and that this means more work output per pound of gas.

Also, as turbine exhaust temperatures rise and compressor outlet temperatures fall it is possible to regenerate over a greater temperature difference. The result is an increase in thermal efficiency of the cycle.

To illustrate the magnitude of these effects an example was worked out for CO₂ and graphite operating between the temperatures and pressures shown on Figure 7 except that below graphite loadings of .5 lb/lb gas the lower pressure was 150 psia instead of 45 psia. The calculations, together with the thermodynamic relations used are contained in the Appendix.

Figure 8 shows how thermal efficiency is raised by the addition of graphite to the point where it closely approaches the Carnot efficiency, which is the theoretical maximum for the upper and lower cycle temperatures used; namely 1300 and 300°F respectively.

Figure 9 shows the increase in power output per pound of gas. This should bring about a considerable reduction in plant size.

Figure 10 shows the effect of mixture density on turbine operating speeds. This is brought about by the fact that, with higher densities, mixture and blade velocities do not have to be as high to get a given amount of power out of a turbine stage. The lower RPM is very desirable as it reduces blade stresses, bearing maintenance, and turbine construction cost.

An interesting thought is that these lower turbine speeds may make it practical to build the often discussed "inside out turbine" which has blades mounted inside of rotating rings. This design is usually considered impractical because stresses are too high in the rings at normal turbine speeds. Ceramic blades would be ideal for this purpose since they would be in compression. In this manner it may be possible to go to much higher top cycle temperatures than are used today.

Nuclear Properties

If made up of good moderators, such as CO₂ and graphite, gas-ceramic mixtures may have sufficient moderating power at the densities attainable to materially reduce the leakage of neutrons out of coolant openings in the reactor core and make a small contribution toward a negative temperature coefficient. Due to the lack of time, the magnitude of these effects has not been studied at this time. Any reactivity due to moderating properties of the mixture can be raised or lowered at will by raising or lowering the mixture pressure in the reactor as this would change the mixture density. This might be useful for control purposes and would tend to make the plant fail-safe.

System Decontamination Properties

The high surface area of the suspended particle of a gas-ceramic mixture compared to the internal surface of piping, heat exchangers, turbine, reactor coolant passages, etc. of the plant may provide an effective diffusion and adsorption trap for gaseous fission products that have diffused through solid fuel element cladding. The rate at which system components become radioactive might be materially reduced by continuously changing the solid constituent of the circulated mixture. Graphite or activated carbon may be useful for this purpose. This would serve to reduce plant maintenance costs and would also provide an answer to a problem which becomes very serious as fuel element temperatures rise.

To get some idea of how effective this is, an experiment has been run to see whether iodine and tellurium are preferentially picked up by activated charcoal at 1300°F in a stainless steel capsule. Results indicate that the stainless steel capsule containing carbon was about 700 times less active on its surface than a similar empty capsule. Reheating the specimens to 300 °F had but little effect on reducing activity but acid washing (HCL) reduced it by a factor of 10.

Erosion and Pluggage

The questions of erosion and heat exchanger pluggage have often been raised in connection with the intended use of these mixtures. The limited experience thus far indicates that neither one is a problem. The 2S aluminum flow nozzle used in the test apparatus has shown no signs of wear after 15 hours of operation with graphite and N_2 passing through it at speeds from 800 to 1150 feet per second.

Figure 11 shows a photograph of the lower tube sheet in the heat exchanger after 12 hours of operation. Out of 150 tubes in the heat exchanger, all tubes appear clean except two hidden under the accumulation of graphite shown here. Another proof of tube cleanliness is that the heat exchanger pressure drop remained the same as before graphite was pumped through it.

It was noticed, however, that the graphite tended to settle out in pockets here and there unless the system was kept very dry. This would not be a problem at the higher temperatures that would be used in the intended power cycle.

Conclusions

The encouraging results obtained by this project lead to the following conclusions:

1. Gas-ceramic mixtures have high heat capacities which are comparable to pressurized water and liquid metal reactor coolants.
2. Suspended particles improve heat transfer rates over that of a gas alone.
3. Thermal efficiency of ideal closed cycle gas turbine cycle can be increased 30 to 45%.
4. Power output of the cycle can be increased as much as 2.5 times.
5. Turbine RPM can be reduced 40% without reducing work output per stage below that which would be had with the suspending gas alone.
6. Suspended particles promise to have significant system decontamination properties.
7. Mixtures of N_2 - graphite and CO_2 - graphite showed no tendency to erode parts of the test equipment.
8. Above mixtures flowed satisfactorily through vertical and horizontal pipes, valves, blowers, and heat exchangers (tube side) in the test apparatus.

In view of the above and the fact that no discouraging aspects have become apparent thus far, it appears that a more intensive investigation of the possibilities of using gas-ceramic mixtures in the manner described in this report is well justified.

The present plans are to continue this project on a part-time basis with

the author spending one day per month at the Ceramic Laboratory, Y-12 for this prupose. All comments and suggestions will be welcome.

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9. Effect of Graphite Loading on Power Output
10. Effect of Mixture Density on Turbine Speed
11. View of Lower Tube Sheet.

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FLOW DIAGRAM ²⁰

Fig. 1--Flow Diagram of Closed Cycle Gas Turbine Nuclear Power Plant
Using a Gas-Ceramic Mixture in Place of a Gas

FLOW DIAGRAM 2/

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Fig. 2--Flow Diagram of Orthodox Closed Cycle Gas Turbine Nuclear Power Plant

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Fig. 3--Test Loop for Gas-Ceramic Mixtures

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Fig 3

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Fig. 4--Effect of Graphite Loading on Heat Transfer

Fig. 5--Variation of heat Transfer Rate and Velocity with Graphite Loading for Constant Pressure Drop

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Fig. 6--Effect of Mixture Heat Capacity on Heat Transfer

24
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150/0

TEMPERATURE (°F)

1300

300

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925

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Fig. 7--T-S Diagram of Ideal Power Cycle with and without Addition of Ceramic Powder to Gas

Fig. 8--Effect of Graphite Loading on Thermal Efficiency

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Power 150%

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Fig. 9--Effect of Graphite Loading on Power Output

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Robert
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4.19
10

Fig. 10--Effect of Mixture Density on Turbine Speed

Reduce
10%

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30

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Fig. 11--View of Lower Tube Sheet

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APPENDIX

Thermodynamics of Gas Suspensions*

The equation of state is clearly

$$V = ZRT/P + v \quad 1$$

where V = volume occupied by 1 lb of gas and the accompanying solid

$$v = w_s/\rho_s \quad 2$$

where v = volume occupied by solid

$$w_s = \text{lb. solid per lb. gas}$$

$$\rho_s = \text{density of solid}$$

Consider the thermodynamic cycle shown below:

The compression will be adiabatic and in the case of an ideal cycle, will be isentropic. For any fluid, in an isentropic compression

$$T_2/T_1 = (P_2/P_1)^{ZR/C} \quad 3$$

provided Z , R , and C do not vary during the compression. In the present case, R is the gas constant per pound of gas, Z is the compressibility, but C is the heat capacity of the mixture,

$$C \text{ (mixture)} = C_p \text{ (gas)} + C_s \text{ (Solid)} w_s \quad 4$$

here defined as the heat capacity of one lb. gas plus w_s lbs. solid/lb gas.

The compression ratio fixes T_2 , but the temperature rise decreases as C increases.

* By L. G. Alexander, ORSORT Faculty

Work done in the compressor, W_c is given by

$$W_c = C(T_2 - T_1)$$

5

Assuming the heating in the reactor is at constant pressure,

$$Q_r = C(T_3 - T_2)$$

6

Where Q is the heat added per pound of gas flowing through system, T_3 and T_2 are outlet and inlet reactor coolant temperatures resp. The cycle is completed by inverting these two processes, and the thermodynamic efficiency is computed in the usual way.

$$\text{Eff.} = \frac{W_T - W_c}{Q_r}$$

where W_T denotes work done by the turbine.

Calculation of Thermodynamic Characteristics

Ideal Cycle - Top Temp		Press; 1300 °F and 1500 psia Bot. Temp. 300 °F					
Graphite Loading Lb/Lb	0	.5	1.0	2.0	3.0	4.0	5.0
<u>A Compression</u>							
1. P_2/P_1	10.0	33.30	33.3	33.3	33.3	33.3	33.3
2. $\log(P_2/P_1)$	2.303	3.507	3.507	3.507	3.507	3.507	3.507
3. C_s	--	.30	.28	.275	.260	.250	.230
4. $W_s C_s$	0	.150	.280	.550	.780	1.000	1.150
5. C_p	.2467	.245	.240	.236	.234	.233	.232
6. C	.2467	.395	.520	.786	1.014	1.233	1.382
7. $.04513/(6) = RZ/C$	.1830	.1143	.0867	.0574	.0445	.0366	.0326
8. (2) X (7)	.4217	.400	.304	.2012	.1560	.1283	.1143
9. $\log - 1(8)$	1.525	1.4935	1.3555	1.223	1.1689	1.177	1.1213
10. $T_2 = 760 \times (9)$	1167	1135	1031	928	888	864	852
11. (10) - 760	407	380	271	168	128	104	92
12. (11) X (6) = Work	100.3	148.0	140.8	131.7	129.9	128.3	127.0
<u>B Expansion</u>							
1. P_1/P_2	10.0	33.3	33.3	33.3	33.3	33.3	33.3
2. $\log P_1/P_2$	2.303	2.507	3.507	3.507	3.507	3.507	3.507
3. C_s	--	.376	.400	.400	.400	.400	.400
4. $W_s C_s$	000	188	400	800	1.200	1.600	2.000
5. C_g	.281	.287	.287	.289	.290	.291	.291
6. C	.281	.475	.687	1.089	1.490	1.891	2.291
7. $.04513/(6) = RZ/C$	.1605	.095	.0657	.04142	.03023	.02383	.01969
8. (2) X (7)	.370	.333	.2303	.1451	.106	.0836	.0690
9. $\log^{-1} (8)$	1.448	1.396	1.2592	1.1565	1.1119	1.0872	1.0714
10. $T_2 = 1760/(9)$	1215	1260	1398	1521	1583	1618	1642

Graphite Loading	0	.5	1.0	2.0	3.0	4.0	5.0
11. 1780 - (10)	545	500	362	239	177	142	118
12. (11) x (6)	153.2	237.2	248.7	260.3	264	268.7	270.2
13. (B-12)-(A-12)= $\frac{\text{Btu}}{\text{lb}}$	52.9	88.2	107.9	128.6	134.1	140.4	143.2
14. Ideal Eff=(13)/(12) (Full Regen.)	34.5	37.2	43.4	49.4	50.9	52.2	52.9
15. Carnot Eff	56.8	56.8	56.8	56.8	56.8	56.8	56.8
16. Engine Eff	60.6	65.5	76.4	87.0	89.6	91.9	93.2
17. Work Ratio	1.0	1.67	2.04	2.44	2.54	2.655	2.709
18. Spec. Vol@1300°F + 1500 psia	.282	.189	.1417	.0943	.0708	.0566	.0471
19. Density lb/ft ³	3.53	5.29	7.06	10.60	14.13	17.66	21.20
20. Spec Vol H ₂ O 1300° 1500 psia	.6759	.6759	.6759	.6759	.6759	.6759	.6759
21. Ft ³ Gas/KW	16.95	11.35	8.52	5.66	4.25	3.40	2.83
22. Ft ³ Steam/KW	6.759	6.759	6.759	6.759	6.759	6.759	6.759
23. KE/LB in Turbine	153.2	158.0	124.0	86.8	66.0	53.6	45.0
24. Corr Velocity	2772	2812	2492	2090	1818	1640	1502
25. G = $\rho \times (24)$	9780	14900	17600	22100	25700	29000	31830
26. G X C	2412	5880	9160	17380	26080	35700	44,000
27. Turbine EX Temp	1215	1260	1398	1521	1583	1618	1642
28. Comp Outlet Temp	1167	1135	1031	928	888	864	852
29. ΔT	48	125	367	593	695	744	790
30. Velocity/Stg for 10 Stgs	875	890	790	662	576	519	475
31. RPM	4190	4200	3775	3160	2750	2480	2270
32. Hoop Stress psi	47,900	49,700	49,100	27,200	21,600	16,750	14,050

Method of Computing Solids Concentration in a Gas-Ceramic Mixture

Using the previously described thermodynamic relations for gas-ceramic mixtures, and assuming particles and gas stay at the same temperature throughout the expansion in the flow nozzle of the test apparatus; the gas flow rate through the flow nozzle and its heat capacity are calculated for a range of solids loadings using the test values of flow nozzle inlet temperature, inlet pressure and throat pressure. An example of this calculation is shown for test N-C-7 in the tabulation below. The value of solids concentration determined by test is the one defining a heat capacity value which equals the heat capacity of the mixture as computed from the heat exchanger test data. (Btu/hr divided by mixture temp drop). This also defines the flow rate of the suspending gas.

Test No. N-C-7

1. W_s/W_g	0	.5	1.0	1.5	2.0
2. P_1	21.65				
3. P_2	11.85				
4. P_1/P_2	1.826				
5. T_1	664				
6. C_s	.20	.20	.20	.20	.20
7. $W_s C_5$	.0	.10	.20	.30	.40
8. C_g	.25	.25	.25	.25	.25
9. C	25	35	45	55	65
10. .0707/(9)	2830	.2022	.1575	.1287	.1089
11. .6015/(10)	.1704	.1216	.09475	.0775	.0655
12. Log^{-1} (11)	1186	1.1295	1.0992	1.0804	1.0676
13. T_2	561	588	604.5	614.5	622.0
14. $T_1 - T_2$	103	76	595	51.5	(44.0)
15. $\Delta h/\text{lb gas}$	25.75	26.20	26.75	28.30	28.60
16. $\Delta h/\text{lb mix}$	25.75	17.45	13.375	11.31	9.53
17. Velocity (Theor)	1135	934	818	753	690
18. Spec. Vol = $T_2/30.95$	1815	1900	19.54	19.85	20.10
19. G (Theor) $\text{lb}/\text{ft}^2 \text{ hr}$	62.50	49.15	41.90	37.90	34.30
20. $W_g = (19) \times 28.5 \text{ lb/hr}$	1780	1400	1194	1080	977
21. (20) $\times$ (9) = WC	445	490	537	594	635

WC from HX =

570

 $W_s = 1.35 W_g = 1070$

Theoretical Value of Clear Gas Heat Transfer Rate

22.	$G = W_g / .1443$	7420
23.	R_e	5520
24.	$R_e^{.8}$	980
25.	$P_r^{.4}$	.865
26.	$h = .10928 \times (24) \times (25)$	9.26
27.	U_{mix} (by test)	16.28
28.	U_{mix} / h	1.76

Physical Characteristics of Test Apparatus

A. Heat Exchanger

Type - Shell and Tube

Surface (Based on Tube I.D.) = 65.2 ft^2

Tubes - 150 1/2" O.D., .4207 I.D. X 48" long, Copper

Tube Sheet Dia - 10"

Materials - Carbon Steel Except for Tubes

Working Pressure - 125 psi both sides

Manufacturer - Bell and Gossett

Total Flow Area Inside Tubes = $.1443 \text{ ft}^2$

B. Flow Nozzle

Material - 2 S Aluminum

Throat Dia - $1.220" \pm .001"$

Connections - 3" ips flanged, both ends

Type - ASME long radius with divergent diffuser section to reduce overall pressure drop to a minimum

Pressure Taps - Upstream 1 Dia. and Throat

C. Blowers

Type - 6 Stage centrifugal

Mfg. - U. S. Hoffman Machinery Corp.

Serial Nos 114372, 54579

Mfgr Type BBA, Frame 41

Size of Connections - 3" Ips flanged

Pressure Rise - 3 Psi with Std. air at inlet

Motors - Normally are 10 H.P. now using 30 HP (440 V 3 phase)

RPM - 3600

Rotameter Measuring Cooling Water Flow to HX

Size No 4 - 1/2"

Tube No 4 - HCF

Rotor No 43-J

Rotor Matl. Stainless Stl.

Rotor Scale 0 to 250

Flow at 0 on scale is .20 gpm sp gr 1.0 liquid

Flow at 250 on scale is 3.10 gpm sp gr 1.0 liquid

Test Data

Test	N-C-1	N-C-2	N-C-3	N-C-4	N-C-5
Date	7/30/55	7/30/55	8/1/55	8/1/55	8/19/55
Time	4:45 PM	5:20 PM	11:38 AM	2:30 PM	12:58 PM
Gas	N ₂	N ₂	N ₂	N ₂	N ₂
Solid	Graphite	Graphite	Graphite	Graphite	Graphite
Slurry Temp to HX-°F	171.0	177.0	186.0	195.0	205.5
Slurry Temp to HX-°F	90.5	97.0	92.0	95.0	102.5
Slurry ΔP Across HX-H ₂ O	3.4	3.0	2.85	2.85	2.77
Water Temp Lv HX-°F	100.0	116.7	104.0	108.5	126.0
Water Temp to HX-°F	64.5	65.5	64.0	63.5	64.0
Water Rotameter Scale Rdng.	142.0	124.0	149.0	139.0	102.5
Nozzle Inlet Press lb/in ² gage	4.75	4.95	5.50	5.90	7.10
Nozzle Throat Press-in. Hg Vac	7.40	6.50	6.90	6.60	5.30
Press @ LP Comp inlet in Hg	1.5	1.3	.75	1.40	3.0
O ₂ Gas% by Vol	0	0	0	0	0

Graphite used in all tests was Dixons Micronized Air Spun

Graphite dried @ 300 °F for minimum of 24 hrs

All gases used in tests with graphite were dried with

Phosphorus Pentoxide and/or Magnesium Perchlorate

Test Data (Cont)

Test	N-C-6	N-C-7	N-C-17	CO ₂ -C-1
Date	8/9/54	8/9/54	9/12/55	9/27/55
Time	3:14 PM	4:20 PM	4:55 PM	11:12 AM
Gas	N ₂	N ₂	N ₂	CO ₂
Solid	Graphite	Graphite	Graphite	Graphite
Slurry Temp to HX - F	2120	203.5	197.0	217.0
Slurry Temp to HX - F	97.0	93.0	101.0	147.0
Slurry Δ P Across HX in H ₂ O	2.77	2.77	3.44	7.30
Water Temp Lv HX °F	100.5	94.0	91.7	92.0
Water Temp to HX °F	62.7	62.7	61.0	63.0
Water Rotameter Scale Rdn	202.0	231.0	210.0	191.0
Nozzle Inlet Press lb/in ²	7.55	6.95	6.35	10.65
Nozzle Throat Press in HG Vac	5.25	5.80	(7.60)	.70
Press @ LP Comp inlet	3.3	2.6	1.7	2.0
O ₂ in Gas, % by Vol	0	0	0	0
Final Wt. of Sampler Ampule	---	---	230.2171	233.6928
Initial Wt. of Sampler Ampule gr-	---	---	226.1591	215.2972
LB H ₂ O Displ. by Flow thru Ampule	---	---	19.0	9.0
Sampling Time-Sec(Approx)	---	---	15.0	15.0
Press of Gas which displaced H ₂ O	---	---	Atm	Atm
Temp of Gas which displaced H ₂ O °F	---	---	88	83

Note: Tests beyond N-C-7 have not been analysed.

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~~UNCLASSIFIED~~Test Data (Cont)

Test	N-0-1	A-0-1	N-0-2	r-0-1	CO ₂ -0-1
Date	7/25/55	7/25/55	7/28/55	7/28/55	7/28/55
Time	9:12 PM	11/57 PM	9:12 PM	1:43 PM	9:35 PM
Gas	N ₂	Air	N ₂	A	CO ₂
Solid	None	None	None	None	None
Slurry Temp to HX °F	197.5	195	192.5	243.0	157.0
Slurry Temp to HX °F	99.0	86.5	94.7	94.0	88.0
Slurry ΔP in HX - "H ₂ O	2.38	2.38	2.55	.94	2.30
Water Temp Lv HX-°F	129.0	129.5	113.5	101.5	97.5
Water Temp to HX °F	64.0	64.5	64.0	63.0	64.4
Water Rotameter Scale Rdngr	79.0	78.0	114.5	172.0	112.5
Nozzle inlet press lb/in ² gage	4.65	4.75	5.10	6.25	3.08
Nozzle Throat Press IN Hg Vacuum	7.50	7.32	7.10	7.15	8.75
Press @ LP Comp. Inlet Hg	--	--	.75	--	--
O ₂ in gas by vol	6.0	--	0	4.3	0

only
HP
Blower
Operating.
10 HP
Motors
not able
to take
load

~~UNCLASSIFIED~~

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