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SUBJECT: The Helium Purification System for the Proposed Pebble Bed Reactor Experiment

TO: A. P. Fraas

FROM: C. D. Scott, B. C. Finney, and J. C. Suddath

ABSTRACT

A helium coolant side-stream purification system consisting of parallel sections for radioactive and non-radioactive de-contamination was designed for the proposed Pebble Bed Reactor Experiment. Primary equipment components are two gas coolers, gas heater, charcoal delay trap, CuO oxidizer, Molecular Sieve adsorber, and full flow filter. The charcoal delay trap is sized to provide a hold-up of 30 minutes for Kr isotopes, 6 hr hold-up for Xe isotopes, and 99.9% retention of iodine isotopes resulting in "de-contamination factors" varying from 1 for Kr^{85} to 556 for I^{131}. Non-radioactive de-contamination will result in a steady state concentration of CO_2 in the coolant of 20.8 ppm or less.

Total cost of the system excluding auxillary equipment and containment is estimated to be $26,690.

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1.0 INTRODUCTION

The helium coolant of any gas cooled reactor will become contaminated with radioactive and non-radioactive gases and solids during the operation of the reactor. Some common sources of these impurities are inleakage of air and water, outgassing of both the graphite reflector and fuel, release of radioactive gases and solids from the fuel, and generation of particulate matter by attrition.

In general, the purification system for the helium coolant must include provisions for removing gaseous and particulate radioactive and non-radioactive impurities.

Radioactive contamination must be kept at a level low enough so that in the event of a maximum credible accident the release of activity will not exceed acceptable limits. It is also desirable to keep the radioactive contamination at a low level so that direct maintenance of certain of the reactor components will be possible and to prevent buildup of neutron poisons.

The main reasons for limiting the non-radioactive contamination in the helium coolant are to prevent chemical corrosion and particulate induced erosion of the various reactor materials and to reduce the effects of poor thermal properties and neutron poisoning due to the contaminants.

Since several of the operations in the purification system require essentially ambient temperature, it will be desirable that the side-stream purification flow rate be as low as possible so that the major portion of the coolant heat is conserved.

2.0 PURIFICATION SYSTEM FLOWSHEET

The purification system will be composed of three major components: (1) fission product delay trap, (2) chemical purification consisting of an oxidizer and adsorber, and (3) an absolute filter (Fig. 2.1).

2.1 Fission Product Delay Trap

A charcoal trap will be used to remove or delay the fission product gases, I_2, Xe, and Kr. The I_2 will be essentially irreversibly removed by the charcoal.[1] Kr and Xe will be delayed as they passes through the charcoal trap due to dynamic adsorption of these gases by charcoal. There is available information on the delay times to be expected[2] in such a trap and if these are compared with the half lives of the fission products of interest, their effective removal by decay in the trap can be determined.

2.2 Chemical Purification

The non-radioactive gaseous contaminants of interest are CO, H_2, hydrocarbons, CO_2, and traces of H_2O. The general criteria used in determining the necessary unit operations for such a system were (1) use of no liquid systems, and (2) use of simple but effective process control systems.

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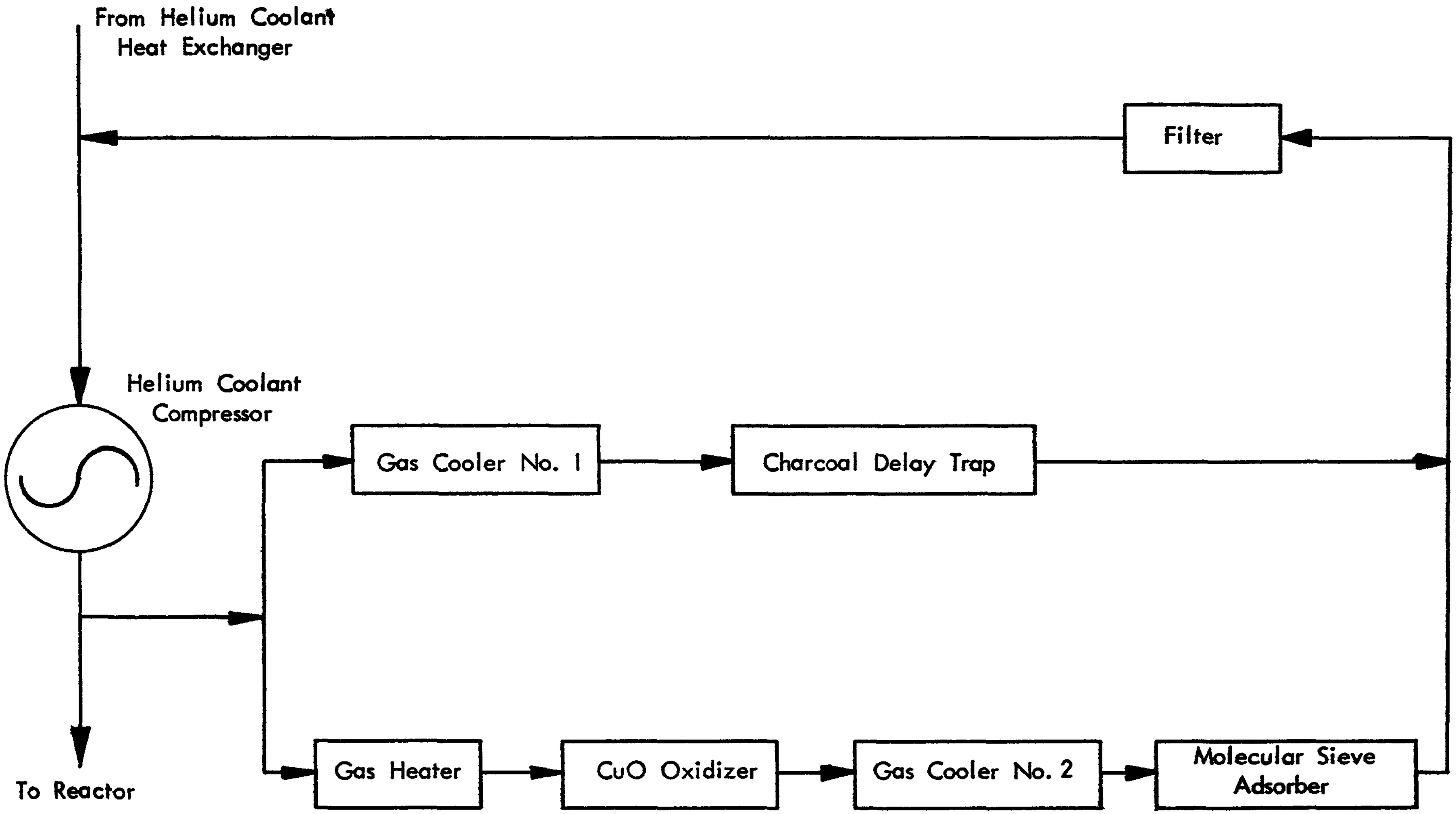

Fig. 2.1. Proposed pebble bed reactor experiment helium coolant purification system.

The scheme to be used is to first oxidize all oxidizable gases (H_2, CO, and hydrocarbons) to CO_2 and H_2O and then remove the CO_2 and H_2O by a sorption process. It was decided to use CuO as the oxidizing agent since early experimental work indicated that it is an excellent oxidizing agent without possibility of oxygen contamination of the purified gas.[3]

As indicated in the flowsheet (Fig. 2.1) the purification side stream to the chemical purification section will be separate from that to the fission product delay trap. This will allow separate, independent use of either or both sections.

2.3 Filters

Particulate matter removed in the coolant will be achieved by high temperature filters in the main coolant stream and by a low temperature (ambient) filter in the purification side-stream. The filter in the purification system will be placed downstream from all other components to protect the main stream coolant from solids generated by attrition in the purification system.

3.0 PURIFICATION SYSTEM CRITERIA

The design of the purification system is dictated by various reactor properties and general criteria relating to operation of the purification system components.

3.1 Reactor Properties Pertinent to Purification System Design

Various properties and requirements of the Pebble Bed Reactor Experiment have a direct bearing on the design of the helium purification system. Many reactor properties have been estimated since the reactor concept is in the early planning stage. Following is a list of the properties which were used in establishing the design of the purification system:

1. The purification side-stream will exit the main coolant stream just after the main stream compressor and it will re-enter the main stream just prior to the compressor (Fig. 2.1). This will give a potential pressure drop of 15 psi in the purification system.

2. The coolant will be helium at approximately 1000 psi with a maximum temperature of 1250°F and a minimum temperature of 650°F.

3. The coolant mass flow rate will be 11.0 lb/sec.

4. The total helium inventory in the system will be 300 ft^3 at 1000 psi and 950°F.

5. Leak rate of the coolant from the reactor will be at a rate of 1% per day.

6. The coolant velocity at the inside reflector wall will be 50 ft/sec.

7. Coolant flow rate through the charcoal fission product delay trap will be 1% of the main coolant flow rate.

8. The fuel shall be UO_2 contained in 1.5-in.-dia graphite spheres.

9. The fuel spheres shall be contained in a cylindrical volume 1.5 ft-dia by 8 ft long.

10. The graphite reflector surface exposed to chemical attack by contaminants in the coolant is that inside surface of the reflector which is a diameter of 1.5 ft and 8 ft long.

11. Total amount of graphite in core excluding fuel spheres is 70,000 lb or 682 ft^3.

12. Allowable burn-up of graphite in core exclusive of fuel spheres is 1% of the total amount (700 lb) in a two-year period of 300 operating days/year.

13. There is a steady state out-gassing rate from the graphite in the core of 0.0003 ft^3 (STP)/ft^3 graphite. The composition of this gas is:

CO_2 - 50%

CO - 10%

H_2O - 15%

Hydrocarbon - 25%

14. Maximum allowable inleakage of H_2O from the main coolant heat exchanger is 0.1 lb/day.

3.2 General Criteria for the Purification System

The following general criteria were established for design of the purification system for the Pebble Bed Reactor Experiment. In many cases they are arbitrary choices. These criteria along with the reactor properties are the complete basis for the design of the purification system.

General Criteria

1. The fission product delay trap will be designed to delay Kr for 1/2 hr and Xe for 6 hr.

2. The charcoal delay trap and the molecular sieve adsorption trap will operate at 85°F.

3. The charcoal used in the delay trap will have properties similar to those presented in CF 59-6-47.

4. Type 5-A Linde Molecular Sieves which are 1/8-in.-dia will be used in the adsorption trap.
5. Harshaw CuO pellets, 1/8-in.-dia, will be used in the oxidizer.
6. The oxidizer will operate at 752°F.
7. Gas heating will be accomplished by electrical heat.
8. Gas cooling will be accomplished by cooling water which will enter the heat exchanger at 75°F and leave at 150°F.
9. The oxidizer and adsorber will be designed to operate continuously for seven operating days without regeneration of the beds.

4.0 CONTAMINATION LEVEL AND PURIFICATION SYSTEM GAS FLOW RATE

The maximum allowable CO_2 contamination level in the coolant was determined to be 20.8 ppm (vol) and the necessary gas flow rate through the non-radioactive purification system was determined to be 0.317% of the total coolant flow.

4.1 Non-Radioactive Gaseous Contamination Level in the Coolant

The non-radioactive, gaseous contamination level in the coolant was determined by the requirement that the amount of graphite burn-out shall not exceed 700 lb/600 days of operation.

It was assumed that all of the H_2O introduced to the coolant by either inleakage or graphite outgassing immediately reacts irreversibly with graphite to form CO,

$$H_2O + C \rightarrow H_2 + CO \qquad (1)$$

and thus contributes to the graphite burnout.

It was further assumed that all carbon-oxygen gases are in the form of CO_2 as the coolant enters the core, and any CO in the coolant as it enters the heat exchanger will be converted completely to C and CO_2 by the reaction,

$$2CO \rightarrow CO_2 + C \qquad (2)$$

Thus, additional graphite burnout can occur by the reaction,

$$CO_2 + C \rightarrow 2CO \qquad (3)$$

in the reactor core after which the reverse reaction (reaction 2) occurs in the heat exchanger which allows transport of carbon from the core to the heat exchanger by the oxygen being recycled by the coolant.

In order to maintain the graphite burnout or carbon transport to a level of 700 lb/600 days it will be necessary to maintain the available oxygen or CO_2 at a low level in the coolant.

It was assumed that the H_2 and hydrocarbons did not contribute to the graphite burnout; however, they should be kept at relatively low levels to prevent change of the thermal properties of the coolant and to reduce the explosion hazard.

The tolerable CO_2 level in the coolant can be determined by equating a reaction rate of the CO_2 with the graphite to the allowable graphite burnup rate,

$$N = B \tag{4}$$

where

N = lb-mols of CO_2 reacting with graphite per square foot of graphite available for reaction per day.

B = allowable graphite burnout by CO_2/day which is 0.0916 lb-mols/day.

In order to determine the CO_2 concentration dependence of the rate of reaction of CO_2, N, it is necessary to determine or assume the apparent rate controlling mechanism of the reaction, $CO_2 + C \rightarrow 2CO$, in the reactor environment.

Antill and Peakall[4] did some work on the CO_2 - C reaction for the British HTGCR, in which they found reaction rates for the reaction at 900-1000°C. The mechanism of the reaction was not determined and the pressure and flow characteristics of their experimental system were not similar to the Pebble Bed Reactor Experiment; therefore, one would hesitate to use their rate data. (It should be noted that use of their data would result in allowable CO_2 levels within a factor of 10 of those determined in this report.)

According to Walker, Ruskinko, and Austin,[5] the three main rate controlling mechanisms of the gas-carbon reaction are (1) chemical reactivity of the solid at relatively low temperatures; (2) combination of (1) and mass transport through the porous solid at intermediate temperatures; and (3) mass transport of the reacting gas and product across a relatively stagnant gas film between solid and main gas stream.

If the graphite temperature is approximately at the estimated maximum coolant temperature of 1250°F the control of the C - CO_2 reaction is probably by method 2. However, to establish a conservative design with allowances for higher graphite temperature and in the absence of kinetics data at conditions close to the actual reactor conditions, it was decided to assume that the control of the C - CO_2 reaction was by mass transfer of the CO_2 through a gas film (method 3).

For mass transfer through the film controlling, the reaction, N, can be expressed by,

$$N = kAp_{CO_2} \tag{5}$$

where, k = mass transfer coefficient, lb-mols/sq ft-day-atm

p_{CO_2} = partial pressure of CO_2 in the coolant, atm

A = surface area of graphite exposed to the coolant, sq ft

The mass transfer coefficient is dependent on various physical properties and fluid dynamics of the system, and the area term is the actual graphite surface exposed to the coolant. According to the system criteria, the mass transfer of carbon from the inside reflector surface is not to exceed 700 lb/600 days; however, it should be pointed out that if this requirement was placed on loss of graphite from the fuel spheres which have ten times as much surface area as the inside reflector surface, the maximum CO_2 concentration in the coolant would have to be maintained at less than 0.2 ppm (vol)(see Appendix). Since this may not be feasible with present technology, it must be assumed that the fuel spheres will be protected by an inert coating which prevents or retards the C - CO_2 reaction.

According to Plautz and Johnstone,[6] heat transfer from a bulk gas to the wall is similar in either a packed or unpacked column. Assuming that this relationship will also hold for mass transfer to the wall in a packed bed, the mass transfer correlations of Scatterfield, Resnick, and Wentworth[7] will be used to predict mass transfer of CO_2 to the reflector wall. In these correlations, the mass transfer coefficient is expressed by,

$$k = \frac{0.021(N_{Re})^{-0.2}(N_{Sc})^{-0.667}\,G}{MP} \qquad (6)$$

where, N_{Re} = Reynold's number

N_{Sc} = Schmidt number

M = average molecular weight of gas

P = total pressure of system, atm

G = mass flow rate lb-mols/ft^2-day

The value for k was found to be 1.76 lb-mols/ft^2-day-atm. Since the inside surface area of the reflector, A, is 37.6 ft^2, total reaction rate is,

$$N = (37.6)(1.76)\,p_{CO_2} = 66.4\,p_{CO_2} \qquad (7)$$

N is to be at a maximum rate of 0.0916 lb-mols/day; therefore, the allowable CO_2 concentration will be,

$$p_{CO_2} = \frac{0.0916}{66.4} = 1.38 \times 10^{-3} \text{ atm} \qquad (8)$$

or at 1000 psi this would be 20.8 ppm of CO_2 by volume.

4.2 Non-Radioactive Gaseous Purification Section Flow Rate

The coolant flow rate of the non-radioactive purification section will be sufficient to remove all of the CO_2 input to the coolant while maintaining a steady state CO_2 level in the main coolant stream of 20.8 ppm or less. The necessary flow rate can be expressed by,

$$P = \frac{I - XL}{XR} \qquad (9)$$

where,

P = coolant flow rate in non-radioactive purification section, lb-mols/day

I = input of impurities resulting in CO_2, lb-mols CO_2/day

L = leak rate of coolant, lb-mols/day

X = mol fraction of CO_2 in main coolant stream

R = removal factor for CO_2 in purification system

In this system, I = 0.0119 lb-mols/day, L = 0.0645 lb-mols/day, and $X = 2.08 \times 10^{-5}$. It was assumed that the CO_2 concentration leaving the purification system was 5 ppm. Therefore, R = (20.8 - 5.0)/20.8 = 0.762. From equation (9)

$$P = \frac{0.0119 - (2.08 \times 10^{-5})(0.0645)}{(2.08 \times 10^{-5})(0.762)} = 755 \text{ lb-mols/day}$$

or P = 0.317% of total coolant flow rate.

5.0 DESIGN OF SYSTEM COMPONENTS

The design of each of the major purification system components has been based on the various reactor requirements, properties, and criteria already established.

The following list shows the specifications of each component:

Component	Type	Size
Charcoal delay traps	Pipe containing granular charcoal	6-in.-ID pipe 65 ft long
Oxidizer	Vessel containing 1/8-in.-dia CuO pellets	14-in.-OD x 20-in. including insulation
Adsorber	Vessel containing 1/8-in.-dia type 5-A Linde molecular sieves	2 ft - 2-in. OD x 5 ft - 4-in. including insulation

(Continued)

Component	Type	Size
Gas heater	Pipe coil with electrical heater	2 ft OD x 2.5 ft
Gas cooler No. 1	Longitudinal finned tube heat exchanger	3.5-in. IPS x 59 ft
Gas cooler No. 2	Longitudinal finned tube heat exchanger	2.5-in. IPS x 42 ft
Low temperature filter	Absolute filter (2 ft^2 area)	12-in. OD x 8-in.

5.1 Design of Charcoal Delay Trap

The preliminary design of the gaseous fission product charcoal delay trap was based on a coolant holdup volume of 300 ft^3 and a side-stream flow rate of 1% of the coolant flow rate (11 lb/sec at 1000 psi and 650°F). It was arbitrarily chosen to size the trap so as to provide an average retention time of 30 minutes for Kr, 6 hours for Xe, and 99.9% retention of I.[1] Determination of the amount of charcoal required is based on the following relationship:(2)

$$m = \frac{Ft_{max}}{K} \qquad (10)$$

where, m = amount of charcoal, g

F = flow rate of diluent gas, cc/min

K = dynamic adsorption coefficient, cc-atm/g-atm

t_{max} = average retention time for fission gas, min

A trap of the following characteristics would satisfy the design specifications:

Amount of charcoal - 184,000 g
Number of units - 1
Length of unit - 65 ft
Diameter of unit - 6 in.
Packing density - 31.2 lb/ft^3
Operating temperature - 85°F
Operating pressure - 1000 psi
Pressure drop - 3 psi

The trap would be effective in a reduction in the activities of the gaseous isotopes; Kr^{87}, Kr^{88}, Xe^{131m}, Xe^{133m}, Xe^{133}, I^{131}, I^{133}, and I^{135} but Kr^{85}

would be unaffected. Analytically the ratio of activity in the loop without side stream holdup to that with side stream holdup is:[8]

$$\frac{A_o}{A} = 1 + \frac{Q_s}{\lambda V_o}\left[1 - e^{-(\lambda K m/Q_s)}\right] \qquad (11)$$

where,

λ is decay constant of the isotope, min^{-1}

V_o is loop holdup volume, cc

Q_s is volume flow rate to side-stream, cc/min

K is dynamic adsorption coefficient, cc-atm/g-atm

m is mass of charcoal, g

It can be further shown that the ratio goes to:

$$\frac{A_o}{A} = 1 + \frac{Q_s E}{\lambda V_o} \qquad (12)$$

for isotopes (iodine) that are trapped by the side-stream with an efficiency, E.

"Decontamination factors" for the gaseous isotopes of interest are presented in the following table:

Isotope	$T_{1/2}$	Loop Activity without* Purification, curies[9]	Loop Activity with Purification, curies	"Decontamination Factor" A_o/A
Kr^{85}	10.3 yr	1.3×10^3	1.3×10^3	1
Kr^{87}	78 m	3.1	1.66	1.86
Kr^{88}	2.77 hr	20	10.4	1.92
Xe^{131m}	12 d	126	9.3	13.5
Xe^{133m}	2.3 d	24	2	12
Xe^{133}	5.27 d	2.79×10^3	214	13
Xe^{135}	9.13 hr	87.2	8.5	10.3
I^{131}	8.05 d	2.2×10^3	4	5.56×10^2
I^{132}	2.4 hr	1.4×10^3	175	8
I^{133}	20.6 hr	2.4×10^2	3.9	61
I^{135}	6.68 hr	57	2.8	20.1
Total		8,247	1,767	

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*Equilibrium activity after 5 years continuous operation and no leakage.

5.2 Design of Oxidizer

From the previous criteria it was decided to design the oxidizer for seven days of continuous service without regeneration. The oxidizer must have a capacity for oxidizing H_2, CO, and hydrocarbons which will be represented by CH_4. The following stoichiometry will be assumed:

$$H_2 + CuO = H_2O + Cu$$

$$CO + CuO = CO_2 + Cu$$

$$CH_4 + 4\ CuO = CO_2 + 2\ H_2O + 4\ Cu$$

Following is a list of the H_2, CO (assuming all C - O_2 compounds may be presented as CO) and CH_4 inputs to the coolant for a period of seven days:

H_2 - 0.0388 lb-mols

CO - 0.0856 lb-mols

CH_4 - 0.00398 lb-mols

From the stoichiometry stipulated and the necessary amount of CuO needed would be 0.1362 lb-mols. Assuming that 50% of the CuO content will be utilized, the amount of CuO needed would be 0.2724 lb-mols or 21.8 lb. At a specific gravity of 1.7 for the CuO pellets this would be a 0.206 ft^3 fixed bed of CuO. This could be contained in a 6-in.-ID vessel 12 in. long. Adding 2 in. of free space at the top and bottom would make it 16 in. long. Since the vessel must be heated to 752°F, it would also be necessary to add electrical heating (approximately 5 kw) and 2 in. of insulation.

5.3 Design of Adsorber

The molecular sieve adsorber was designed for a 7-day continuous operation to absorb 0.0895 lb-mols of CO_2 and 0.0470 lb-mols of H_2O. According to the Linde Company[10,11], dynamic loading of the sieves should be 1/2 of the equilibrium loading. (Loading is defined as lb of H_2O or CO_2 absorbed per 100 lb of molecular sieves). The equilibrium loading on Type 5A Molecular Sieves for H_2O at < 0.5 ppm is approximately 10 lb/100 lb of sieves[11] and the equilibrium loading for CO_2 at 5 ppm is 2.7 lb/100 lb of sieves.[10] On this basis the adsorber will need $100/(10/2) = 20$ lb of sieves for each lb of H_2O and $100/(2.7/2) = 74.2$ lb of sieves for each lb of CO_2 adsorbed. This gives a total of 310 lb of Type 5A Molecular Sieves needed. A vessel 1.5-ft-ID and 4 ft long with 6 in. additional free space would be suitable for the fixed bed of molecular sieves. There must also be available sufficient electrical heating to heat the bed to 600°F for regeneration (approximately 5 kw) and 2 in. of insulation would be desirable.

5.4 Design of Gas Heater

A gas heater capable of heating the coolant up to 752°F for use in the oxidizer will be necessary. A coil of 1-1/2-in.-ID tubing with an 8-in. coil diameter heated by an electrical furnace will be used as a basis for this gas heater. (For calculation it is assumed that the tube wall temperature is 800°F). The heater must be capable of heating 125 lb/hr of helium from 600°F to 752°F for a total heat load of 25,960 Btu/hr (approximately 7-1/2 kw of electrical heat). The total heating surface necessary will be 5.68 sq ft or 14.8 ft of 1-1/2-in. tubing or 10 turns in the coil[12] which would result in about 14 in. of coil length. The over-all dimensions of the unit including electrical furnace would be 24-in.-OD x 30 in. long.

5.5 Design of Purification System Gas Coolers

The effectiveness of charcoal to adsorb gaseous fission products varies inversely with temperature and consequently it is necessary to cool the purification side-stream to minimize the size of charcoal trap required. It is also necessary to cool the gas entering the molecular sieves, for the same reason. Longitudinal fin double pipe heat exchangers were sized as gas coolers 1 and 2.

Gas Cooler No. 1

Assume a heat exchanger consisting of 1-1/2 IPS inner pipe with 24-20 BWG x 1/2-in. fins and a 3 IPS shell will be used to cool 0.11 lb/sec of helium from 650°F to 85°F using water from 75°F to 150°F flowing countercurrent to the helium as the cooling medium. The heat transfer area required is determined by the following:

$$Q = UA\Delta t \qquad (13)$$

where,

Q = heat transferred, Btu/hr

U_{di} = over-all heat transfer coefficient based on inside of tube including fouling factors, Btu/hr-ft^2-°F

A_i = inside surface area, ft^2

Δt = L.M.T.D., °F

To cool 0.11 lb/sec of helium from 650°F to 85°F requires the removal of 277,000 Btu/hr, Q. For this system, U_{di} is 89 Btu/hr-ft^2-°F and Δt_{LMTD} is 125°F. The inside surface area, A_i, required is 25 ft^2 which is equivalent to 59 ft of 1-1/2 IPS.

Gas Cooler No. 2

Gas cooler No. 2 is sized to cool 125 lbs/hr of helium from 752°F to 85°F using 1,380 lbs/hr of water from 75°F to 150°F flowing countercurrent to the helium as the cooling medium. It is assumed that a double pipe heat exchanger consisting of 3/4 IPS inner pipe with 18 0.024-in. thick x 0.5-in. fins and a 2-1/2 IPS outer shell will be used. To handle a heat load of 103,500 Btu/hr, Q, an area, A_1, of 9 ft^2 is required which is equivalent to 42 ft of 3/4 IPS.

5.6 Low Temperature Filter

The low temperature filter will handle the total side stream flow of 0.145 lbs He/sec to remove particulates before returning to the main coolant stream. A flow velocity of 6 ft per min through absolute filters is recommended for highest efficiency but with pleated filters that are 4 inches deep a face velocity of 50 ft per min is equivalent to 6 ft per min. Therefore, a filter size of 8-in.-dia x 4-in. would be sufficient.

6.0 OPERATION AND MAINTENANCE

An advantage of the proposed side stream purification system is the simplicity of operation. Essential components of the system are two-double pipe longitudinal fin heat exchangers, charcoal delay trap (pipe filled with charcoal), electrical gas heater, oxidizer (heated pipe filled with CuO pellets), a Molecular Sieve adsorber vessel filled with absorbent, full flow filter, and appropriate flow regulators and temperature controls. The system will utilize the helium coolant loop pressure drop for fluid flow.

Since there are no moving components, it is expected that the system would be essentially maintenance free. However, it would probably be necessary to regenerate the CuO oxidizer and molecular sieve after approximately each 7 days of reactor operation. To accomplish this the oxidizer will be removed from service and regenerated with air for approximately 8 hours at operating temperature and the absorber will be regenerated by purging with dry air at atmospheric pressure and 600°F for approximately 8 hours. The life of the charcoal delay trap would depend on the poisoning effect of the iodine and fission gas daughter products of which there is no experimental data at the present time. It is estimated that the life of the charcoal,CuO, and Molecular Sieves will exceed 2 years. If it should become necessary to perform some maintenance on the system, the activity level would dictate whether this should be done directly or remotely.

In the event the reactor was shut down and it was desireous to clean-up the entire helium coolant inventory, this could be done by flowing the coolant through the purification system to a holdup vessel or the coolant could be cleaned by recirculation through the purification system.

An on-stream gas adsorption chromatograph could be used to determine the effectiveness of the chemical purification system during operation.

7.0 COST ESTIMATE OF PURIFICATION SYSTEM

The cost estimate for the coolant purification system was prepared for the installed equipment and initial chemical reagents only and does not include the enclosure or auxiliary services. The cost estimating procedure used is a modification of the one presented by Aries and Newton[13] in which the purchase cost of major process equipment is used to determine the cost of other components of the facility by use of factors which have been empirically determined. The total cost of the purification system was determined to be $26,690.

7.1 Purchase Cost of Major Process Equipment

Major process equipment was decided to be any piece of process equipment whose total installed cost was greater than $300. There is a total of 10 such pieces of equipment (Table 7.1 and Fig. 7.1) which have a total purchase cost of $8080.

7.2 Initial Cost of Chemical Reagents

The chemical reagents which are necessary for initial charging of the equipment in the purification system are activated charcoal, CuO, and molecular sieves. The total cost of this initial charge is $888 (Table 7.2). It is estimated that this material will be effective for a minimum of 2 years.

7.3 Total Cost of the Facility

Total facility cost was determined by use of the factors given by Aries and Newton in which the cost of equipment installation is 43% of the purchase equipment cost, piping is 36%, instrumentation is 50%, insulation is 8%, and electrical is 15% (Table 7.3). Addition of initial reagent cost results in a physical plant cost of $21,360 and addition of 25% for contingency results in a total facility cost of $26,690.

8.0 RESEARCH AND DEVELOPMENT REQUIREMENTS

It was necessary in the preliminary design of the helium coolant purification system to make a number of assumptions because of lack of complete design data. Following is a brief list of the areas in which more complete data is required so as to facilitate a more rigorous design of a purification system:

a. Dynamic adsorption of Kr, Xe, and I on charcoal at relatively high pressures (1000 psi) including the effect of iodine poisoning.

b. Kinetics of oxidation by CuO.

c. Kinetics of co-sorption of H_2O and CO_2 by Molecular Sieves at high pressures and low H_2O and CO_2 levels.

d. Kinetics and reaction mechanism of the graphite-gas reactions at pressure, temperature, and flow rates of interest.

e. Kinetics of the graphite mass transfer reaction $2CO \rightarrow C + CO_2$ at conditions of interest.

f. Filter efficiency for high temperature application and data on circulating particule activity.

Table 7.1 Specifications and Purchase Cost of Major Process Equipment for Purification System

Equipment Number (Fig. 7.1)	Description	Size	Material of Construction	Maximum Temperature °F	Maximum Pressure psi	Material Flowrate, lb/sec	Purchase Cost for 1960	Cost Reference
1	Gas cooler, finned tube	3-1/2-in.-OD, 59 ft long with 148 ft^2 heat transfer area	mild steel	650	1000	0.110	$730	13, p. 50
2	Charcoal delay trap	6-in.-ID x 65' long with 6 6-in. fittings	mild steel	85	1000	0.110	580	13, p. 89
3	Filter, absolute	Two each with 2 ft^2 filter media in 12-in.-OD x 8" long enclosure	ceramic	85	1000	0.1447	370	14
4	Gas heater, tube coil in electric furnace	26 ft of 1-1/2-in. tube in 8" coil w/7-1/2 KW of electric heat over-all dimensions 24-in.-OD x 30"	mild steel	1500	1000	0.0347	750	15
5	Oxidizer vessel	6-in.-ID x 16" extra heavy pipe w/4 fittings	mild steel	752	1000	0.0347	240	13, p. 89
6	Oxidizer heater	5 KW	--	1500	--	--	580	15
7	Gas cooler, finned tube	2-1/2-in.-OD, 42 ft long with 74 ft^2 heat transfer area	mild steel	752	1000	0.0347	400	13, p. 50
8	Adsorber vessel	18-in.-ID x 54-in. long extra heavy pipe w/4 fittings	mild steel	600	1000	0.0347	1350	13, p. 89
9	Adsorber heater	5 KW	--	1500	--	--	580	15
10	Chromatograph, gas adsorption	---	--	100	30	--	2500	15
			Total Purchased Equipment Cost				$8080	

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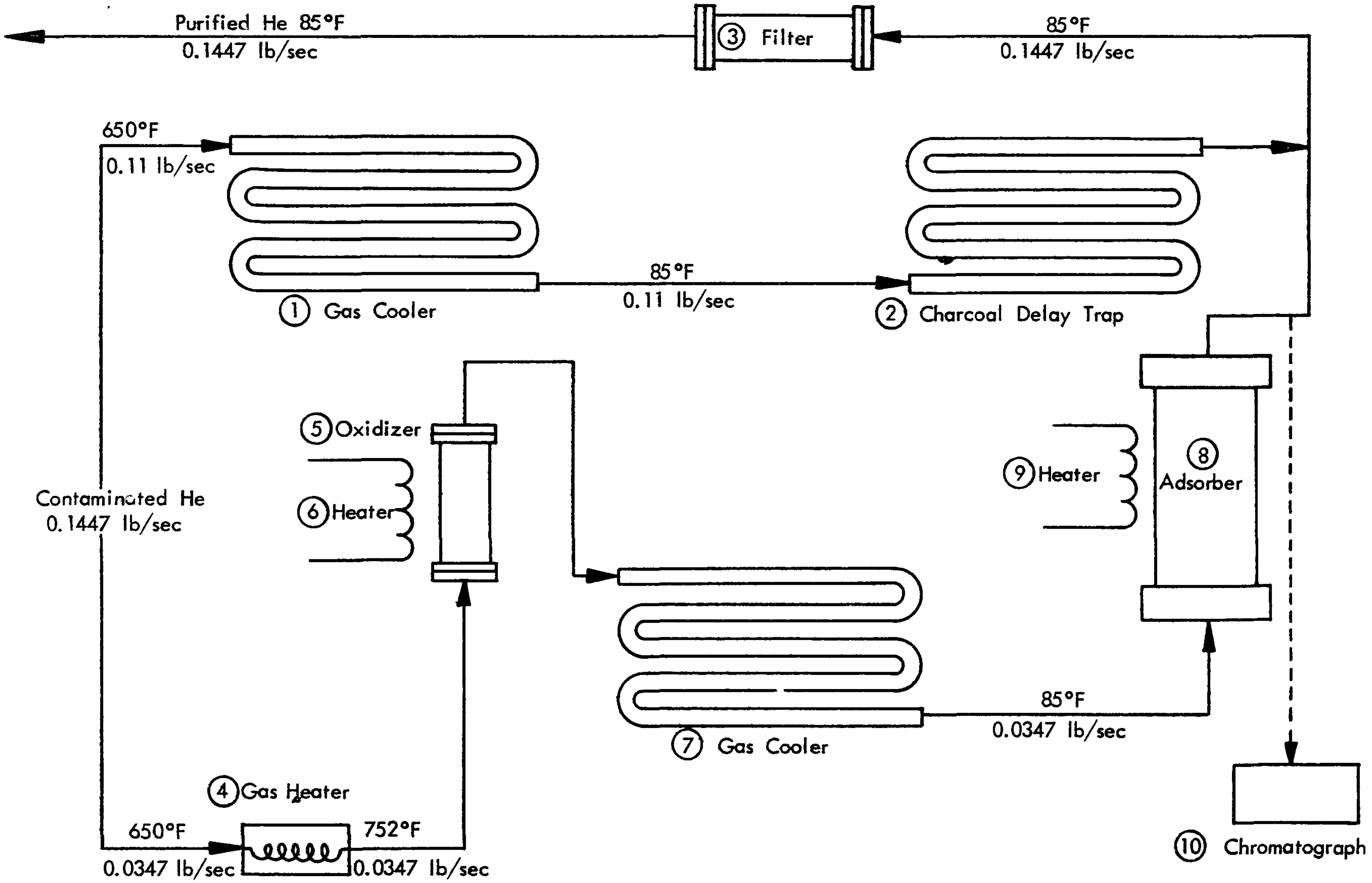

Fig. 7.1. Pebble bed reactor experiment coolant purification system flowsheet showing major process equipment.

Table 7.2 Cost of Initial Chemical Reagents

Reagent Description	Amount, lbs	Unit Cost, $/lbs	Total Cost	Cost Reference
Type PCP activated charcoal, 6-16 mesh	405	0.51	$206	17
CuO pellets, 1/8"-dia	22	3.50	77	18
Type 5A molecular sieves, 1/8"-dia	310	1.95	605	19
	Total Reagent Cost		$888	

Table 7.3. Total Cost of Purification Facility*

Purchased Equipment Cost	$8,080
Installation (43% of purchased equipment cost)	3,580
Piping (36% of purchased equipment cost)	2,910
Instrumentation (50% of purchased equipment cost)	4,040
Insulation (8% of purchased equipment cost)	650
Electrical (15% of purchased equipment cost)	1,210
Initial chemical reagents	890
Physical facility cost	$21,360
Contingency (25% of physical facility cost)	5,330
Total cost of facility	$26,690

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* Does not include cost of building, enclosures, utilities, etc.

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3. C. D. Scott, "Oxidation of Hydrogen and Carbon Monoxide in Helium by Use of CuO. I. Preliminary Results", ORNL-CF-60-7-26 (1960).

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19. Oak Ridge National Laboratory Purchase Order A-114285, December 21, 1959.

10.0 APPENDIX

10.1 Calculation of Graphite Burn-Out of Fuel Spheres

Since burn-out of graphite can occur by the C - CO_2 and C - H_2O reactions, it is desirable to determine the maximum allowable CO_2 content of the coolant which will result in an acceptable graphite loss from the fuel spheres. Although an acceptable graphite loss is not known, for purposes of comparison with acceptable reflector losses it was assumed that 700 lbs/600 operating days would represent an acceptable loss (this is probably too high).

Assuming that all H_2O input to the reactor results in complete reaction with graphite by,

$$H_2O + C \rightarrow H_2 + CO \qquad (1)$$

the acceptable graphite loss by the CO_2 reaction,

$$CO_2 + C \rightarrow 2CO \qquad (2)$$

would be 0.0916 lb-mols/day.

Since the fuel spheres may be at a relatively high temperature (> 1850°F), the probable reaction rate controlling mechanisms will be by mass transfer through the gas film surrounding the sphere (Section 4.1).

Total mass transfer to the fuel spheres can be represented by the equation,

$$N = k_g A p_{CO_2} \qquad (3)$$

where;

k_g = mass transfer coefficient, lb-mol/sq ft-day-atm

p_{CO_2} = partial pressure of CO_2 in the coolant, atm

A = external surface area of the fuel spheres, sq ft

From correlations of Brown(1) for packed beds of solids,

$$k_g = \frac{JG}{MP} (N_{S_c})^{-2/3} \qquad (4)$$

---

(1) G. G. Brown, Editor, "Unit Operations", John Wiley and Sons, New York, 1950.

where,

J = dimensionless factor dependent on Reynolds number

G = mass flow rate, lb-mols/ft^2-day

M = average molecular wt of gas

N_{S_c} = Schmidt number

P = total pressure of the gas, atm

For a mass flow rate of 11 lbs/sec or 23,000 lb-mols/day of helium at 1000 psi and 1250°F through a 1.5-ft-dia tube filled with 1.5-in.-dia spheres with a void fraction of 39%, the modified Reynolds number (D_pG/μ) is 48,500 and the extrapolated value for J from Brown(1) is 0.0157.

The Schmidt number is,

$$N_{S_c} = \frac{\mu}{\rho D_G} \qquad (5)$$

where,

μ = viscosity of gas, cm-sec/g

ρ = density of gas, g/cc

D_G = diffusivity of CO_2 through He, cm^2/sec

The viscosity of the gas is 0.000420 cm-sec/g(2) (disregarding pressure effects). Assuming helium acts as an ideal gas, the density is 0.00349 g/cc. The diffusion coefficient was calculated to be 0.204 cm^2/sec by the method presented by Reed and Sherwood(3). Thus, the Schmidt number is,

$$N_{S_c} = \frac{0.000420}{(0.204)(0.00349)} = 0.598$$

The mass transfer coefficient is,

$$k_g = \frac{(0.0157)(236,000)(0.598)^{-2/3}}{(4)(68)} = 19.2 \text{ lb mols/ft}^2\text{-day-atm}$$

The allowable partial pressure of CO_2 is given by,

$$p_{CO_2} = N/k_gA \qquad (6)$$

---

(2) Handbook of Chemistry and Physics, 31st Ed. Chemical Rubber Publishing Co., 1949.

(3) R. C. Reid and T. K. Sherwood, "The Properties of Gases and Liquids", McGraw-Hill Book Co., p. 268, New York, 1958.

Surface area of the 1.5-in.-dia balls in a cylindrical column 1.5-ft-dia x 8-ft is 413 ft^2.

$$\text{Therefore, } p_{CO_2} = \frac{0.0916}{(19.2)(413)} = 1.15 \times 10^{-5} \text{ atm}$$

or at 68 atm of pressure, the allowable CO_2 concentration would be

$$1.15 \times 10^{-5}/68 = 0.169 \times 10^{-6} \text{ or } 0.169 \text{ ppm (vol)}$$

10.2 Calculations Used in Determination of Maximum CO_2 Level

Area of Reflector

It is assumed that all graphite loss by the reaction,

$$CO_2 + C \rightarrow 2CO \tag{1}$$

occurs from the surface reaction of the coolant-contained CO_2 and the inside wall of the reflector (1.5-ft-dia x 8-ft long). Thus, the amount of surface available for the reaction is,

$$A = \pi(1.5)(8) = 37.6 \text{ ft}^2$$

Graphite Burn-Out by H_2O

Acceptable graphite burn-out is 700 lbs/600 days or 0.0973 mols/day. Since it is assumed that all H_2O input is consumed by the reaction,

$$H_2O + C \rightarrow H_2 + CO \tag{2}$$

the amount of graphite burn-out due to equation (1) would be the difference between the total 0.0973 lb mols/day, and the amount consumed by the H_2O - C reaction (equation 2).

A H_2O input of 0.0057 lb mols/day to the system is due to 0.1 lb/day inleakage and 0.000045 SCF/hr-ft^3 from the outgassing of 682 ft^3 of graphite. Thus, the allowable burn-out of graphite by CO_2 is

$$0.0973 - 0.0057 = 0.0916 \text{ lb-mols/day}$$

Reynolds Number

The Reynolds number, N_{Re}, for the flow systems was assumed to be that for gas flowing at an average velocity of 50 ft/sec in the 1.5-ft-dia tube or a mass flow rate of 5.32 g/sec-cm^2. Since the viscosity is 0.000420 cm-sec/g (Section 10.1) and the diameter of the tube is 1.5 ft or 45.7 cm,

$$N_{Re} = \frac{DG}{\mu} = \frac{(45.7)(5.32)}{0.000420} = 583{,}000 \tag{3}$$

10.3 Design Calculations for Charcoal Delay Trap

Design of the charcoal delay trap is based on the criteria of a 30 min hold-up of Kr, 6 hour hold-up of Xe, and 99.9% retention of iodine, helium flow rate to the side stream purification system of 0.11 lbs/sec (1% of helium coolant flow rate) at 1000 psi, and a trap operating temperature of 85°F. The helium volumetric flow rate is:

$$\frac{0.11 \text{ lb}}{\text{sec}} \times \frac{1 \text{ lb mol}}{4 \text{ lb}} \times \frac{359 \text{ ft}^3}{\text{lb-mol}} \times \frac{545}{492} \times \frac{14.7}{1000} = 0.17 \text{ ft}^3/\text{sec}$$

$$\frac{0.17 \text{ ft}^3}{\text{sec}} \times \frac{28{,}300 \text{ cc}}{\text{ft}^3} \times \frac{60 \text{ sec}}{\text{min}} = 282{,}000 \text{ cc/min}$$

Weight of charcoal, gms, required to obtain the desired delay time, 30 min, for Kr is determined by the following relationship:

$$t_{max} = \frac{Km}{F}^{(1)}$$

where,

t_{max} = retention time, 30 min

K = dynamic adsorption coefficient, 46 cc/g for Kr(2)

m = mass of charcoal required for 30 min retention time

F = diluent gas (helium) flow rate, 282,000 cc/min

$$m = \frac{30 \times 282{,}000}{46}$$

$$= 184{,}000 \text{ g}$$

It is assumed that 6-18 mesh charcoal with a packing density of 31.2 lbs/ft^3 will be contained in a 6 IPS.

The length of 6 IPS required is:

$$\frac{184{,}000}{31.2 \times 454 \times 0.088} = 65 \text{ ft}$$

The modified Reynolds number, Re, establishes whether the flow is viscous or turbulent.

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1. W. E. Browning, R. E. Adams, and R. D. Ackley, "Removal of Fission Product Gases from Reactor Off-Gas Streams by Adsorption", ORNL-CF-59-6-47 (1959).
2. Dynamic adsorption coefficient of 46 cc/g at 1000 psi for Kr was determined by extrapolation of 0-400 psi data supplied by W. E. Browning of Oak Ridge National Laboratory.

$$Re = \frac{D_p V_o \rho}{\mu}^{(3)}$$

where,

D_p = average particle diameter, 0.01 ft

V_o = superficial velocity, 0.85 ft/sec (empty pipe)

ρ = density of helium at 1000 psi and 85°F, 0.69 lb/ft^3

μ = viscosity, 0.018 x 0.672 x 10^{-3} lb/ft-sec

$$Re = \frac{0.01 \times 0.85 \times 0.69}{0.018 \times 0.672 \times 10^{-3}}$$

$$= 484 \text{ (viscous flow)}$$

Pressure drop in the charcoal trap is determined using the expression presented by Chilton and Colburn.(4)

$$\Delta P = \frac{0.97\ A_f Z L G_o}{\rho D_p^2}$$

where,

ΔP = pressure drop, inches of H_2O

A_f = wall effect, 1 for granular beds in which the voids are not excessive

Z = viscosity, 0.018 centipoises

L = length of bed, 65 ft

G_o = mass flow rate based on cross sectional area of empty tube, 0.586 lb/ft^2-sec

ρ = density, 0.68 lb/ft^3

D_p = average diameter of particle, 0.11 inch

$$\Delta P = \frac{0.97 \times 0.018 \times 65 \times 0.586}{0.69 \times 0.11^2}$$

$$= 79.6 \text{ inches of } H_2O$$

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3. J. N. Perry, Editor, Chemical Engineering Handbook, 3rd Ed., p. 393, McGraw-Hill, New York (1950).
4. T. H. Chilton and A. P. Colburn, Ind. Eng. Chem., 23, pp. 913-19, 1931.

Since the helium flow is in the viscous region the pressure drop, ΔP, varies linearly with the mass flow, G_O, and length of bed. Therefore, the pressure drop could be decreased by a factor of 4 by using two parallel traps each 32.5 ft long.

Analytically the ratio of activity in the loop without side stream purification to that with side stream purification (de-contamination factor) is:

$$\frac{A_o}{A} = 1 + \frac{Q_s}{\lambda V_o}\left[1 - e^{-(\lambda Km/Q_s)}\right] \qquad (5)$$

where,

A_o = activity of loop without purification

A = activity of loop with purification

λ = decay constant of the isotope, min^{-1}

V_o = volume holdup of coolant loop, cc

Q_s = volume flow rate to side stream, cc/min

K = dynamic adsorption coefficient, cc-atm/g-atm

m = mass of charcoal, g

It can further be shown that the ratio goes to,

$$\frac{A_o}{A} = 1 + \frac{QE}{\lambda V_o} ;$$

for isotopes (iodine) that are trapped by the side stream with an efficiency, E.

Calculated reduction in activity for Kr^{87} is:

Q_s = 4700 cc/sec for helium

$V_o = 84.9 \times 10^5 \text{ cm}^3$

K = 46 cc/g for Kr at 1000 psi and 85°F

$\lambda = 14.8 \times 10^{-5} \text{ sec}^{-1}$ for Kr^{87}

$m = 18.4 \times 10^4$ g

---

5. J. C. Suddath, "EGCR In-Pile Loop Side Stream Processing", ORNL-CF-60-6-7 (1960).

$$\frac{A_o}{A} = 1 + \frac{4.7 \times 10^3}{84.9 \times 10^5 \times 14.8 \times 10^{-5}} \left[1 - e^{-\left(\frac{46 \times 18.4 \times 10^5 \times 14.8 \times 10^{-5}}{4.7 \times 10^3} \right)} \right]$$

$$= 1 + \frac{1 - e^{-0.266}}{0.266}$$

$$= 1 + 0.87$$

$$= 1.87$$

Calculated reduction in activity for I^{131} at an E of 0.999 is:

$$\frac{A_o}{A} = 1 + \frac{4.7 \times 10^3 \times 99.9 \times 10^{-2}}{99.6 \times 10^{-8} \times 84.9 \times 10^5}$$

$$= 1 + 555$$

$$= 556$$

10.4 Design Calculations for the Heat Transfer Area in the Gas Heater

It is assumed that electrical heat at 1500°F will heat an 8-in.-dia coil of 1.5-in.-dia tubing to a wall temperature of 800°F which will further heat 125 lbs He/hr from 600°F to 752°F. Since helium has a heat capacity of $C_p = 1.24$ Btu/lb-°F,(1) the necessary heat load on the heater, Q, is,

$$Q = (125)(1.24)(752-600) = 23,600 \text{ Btu/hr}$$

After adding 10% for heat losses, the necessary amount of heat transfer to the gas is 25,960 Btu/hr. The heat transfer coefficient is given by the equation,

$$h = \frac{16.6\,(C_p)(G')^{0.8}}{(D_i)^{0.2}} \quad (2)$$

where,

h = heat transfer coefficient Btu/ft^2-hr-°F

C_p = specific heat of gas, Btu/lb-°F

G' = mass velocity, lb/sec-sq ft

D_i = inside diameter of tube, inches

G' will be $0.0347/\pi(0.0625)^2 = 2.82$ lb/sec-ft^2 and $D_i = 1.5$ inches, therefore,

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1. A. C. S., "Thermodynamic Properties of the Elements," Advances in Chemistry Series 18, A.C.S., Washington, 1956.
2. J. H. Perry, Editor, "Chemical Engineers Handbook", 3rd Ed. McGraw-Hill, New York, 1950.

$$h = \frac{(16.6)(1.24)(2.82)^{0.8}}{(1.5)^{0.2}} = 43 \text{ Btu/ft}^2\text{-hr-°F}$$

Since the total heat transferred, Q, is

$$Q = hA(\Delta T)_{Lm}$$

where,

A = area of the tube wall, ft^2

ΔT_{Lm} = log mean change in temperature, °F

Q = total heat transferred, Btu/hr

Heat transfer area can be found from,

$$A = Q/(h)(\Delta T_{Lm})$$

The log mean ΔT will be,

$$\Delta T_{Lm} = \frac{(800 - 600) - (800 - 752)}{\ln[(800 - 600)/(800 - 752)]} = 106\text{°F}$$

therefore, A will be

$$A = 25960/43 \times 106 = 5.68 \text{ ft}^2$$

10.5 Size Determination of Gas Coolers

Both gas coolers were sized in a similar manner. Gas cooler No. 1 was sized to cool 0.11 lbs/sec (1% of primary loop) of helium at 1000 psi from 650°F to 85°F using water at 75° to 150°F flowing countercurrent to the helium as the cooling medium. It was assumed that a double pipe heat exchanger consisting of 1/2 IPS inner pipe with 24-20 BWG x 1/2 inch longitudinal fins and a 3 IPS outer shell will be used. The design calculations follow the example presented by Kern.(1)

Heat balance:

$$Q_{He} = W\ Cp\ \Delta t$$

where,

Q_{He} = heat transferred, Btu/hr

W = weight of helium, 396 lbs/hr

Cp = heat capacity of helium, 1.24 Btu/lb

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1. Donald Q. Kern, "Process Heat Transfer 1st edition, McGraw-Hill Book Co., Inc., New York, pp. 530-39, 1950.

Δt = temperature difference, 565°F

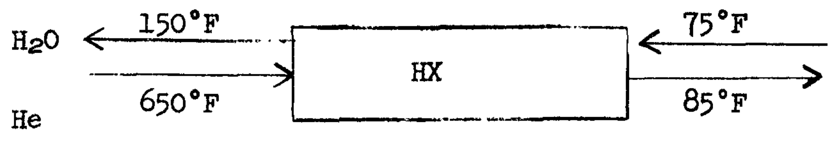
$$Q = 0.11 \times 3600 \times 1.24 \times 565$$

$$= 277{,}000 \text{ Btu/hr}$$

$$W_{H_2O} = Q/Cp\Delta t$$

$$= 277{,}000/1 \times 75$$

$$= 3{,}700 \text{ lbs/hr}$$



$$\text{LMTD} = \frac{(650-150) - (85-75)}{\ln \frac{658 - 150}{85 - 75}}$$

$$= 125°\text{F}$$

Shell Side Calculations

3 in. IPS, ID = 3.068 in.

1.5 in. IPS, ID = 1.90 in.

Fin cross section, 20 BWG, 1/2 in. high = 0.035 x 0.5 = 0.0175 in^2

Annulus cross sectional area:

$$A_a = \left(\frac{\pi}{4} \times 3.068^2 - \frac{\pi}{4} \times 1.90^2 - 24 \times 0.0175\right)$$

$$= 4.13 \text{ in}^2 = 0.0287 \text{ ft}^2$$

Wetted Perimeter:

$$= (\pi \times 1.90 - 24 \times 0.035 + 24 \times 2 \times 0.5)$$

$$= 29.13 \text{ in.}$$

Equivalent diameter:

$$d_e = \frac{4 \times A_a}{\text{wetted perimeter}}$$

$$= \frac{4 \times 4.13}{29.13}$$

$$= 0.57 \text{ in.}$$

$$D_e = \frac{0.57}{12} = 0.0475 \text{ ft}$$

Helium mass flow rate:

$$G_a = \frac{W}{a_a}$$

$$= \frac{0.11 \times 3,600}{0.0287}$$

$$= 13,800 \text{ lbs/hr-ft}^2$$

Viscosity of helium at 365°F and 1 atm

$$\mu = 0.027 \text{ centipoise} \times 2.42 = 0.0655 \text{ lb/hr-ft}$$

Reynold's number:

$$Re_a = \frac{DeG_a}{\mu}$$

$$= \frac{0.0475 \times 13,800}{0.0655}$$

$$= 10,000$$

$$j_f = 38$$

Thermal conductivity of helium:

$$k = 13.9 \frac{\text{kilo-erg}}{\text{cm}^2 - \text{sec}(°\text{C},\text{cm}^{-1})^{-1}}$$

$$= 0.08 \frac{\text{Btu}}{\text{hr-ft}^2\text{-°F/ft}}$$

Fin coefficient:

$$h_f = j_f \frac{k}{De} \left(\frac{Cu}{k}\right)^{1/3}$$

$$= \frac{38 \times 0.08}{0.0475} \left(\frac{1.24 \times 0.0655}{0.08}\right)^{1/3}$$

$$= 64$$

Fouling factor:

$$R_{do} = 0.003 \qquad h_{do} = 333$$

$$h_f^1 = \frac{h_{do} h_f}{h_{do} + h_f}$$

$$= \frac{333 \times 64}{333 + 64}$$

$$= 53.7$$

h^1_{fi} = 200, fin side coefficient adjusted to inside tube

<u>Tube Side Calculations</u>

$$D_t = \frac{1.61}{12} = 0.134 \text{ ft}$$

$$A_t = \frac{\pi \times 0.134^2}{4}$$

$$= 0.0142 \text{ ft}^2$$

$$\mu_{H_2O} = 0.64 \times 2.42 = 1.55 \text{ lb/hr-ft}^2$$

$$G_t = \frac{3700}{0.0142} = 250{,}000 \ \frac{\text{lb}}{\text{hr-ft}^2}$$

$$V_t = \frac{250{,}000}{3600 \times 62.4}$$

$$= 1.11 \text{ ft/sec}$$

Reynold's number:

$$Re_t = \frac{D_t G_t}{\mu}$$

$$= \frac{0.134 \times 250{,}000}{1.55}$$

$$= 21{,}600$$

$$h_i = 380 \times 0.81 = 308$$

$$h_{di} = 333$$

$$h_i' = \frac{308 \times 333}{308 + 333}$$

$$= 160$$

Over-all design coefficient based on inside of tube, U_{Di}:

$$U_{Di} = \frac{h'_{fi} \ h'_i}{h'_{fi} + h_i}$$

$$= \frac{200 \times 160}{200 + 160}$$

$$= 89$$

Determination of inside area required:

$$A_i = \frac{Q}{U_{Di}\Delta t_{LMTD}}$$

$$= \frac{277,000}{89 \times 125}$$

$$= 25 \text{ ft}^2$$

Inside surface area of 1-1/2 in. IPS:

$$= 0.421 \text{ ft}^2/\text{ft}$$

Determination of length of 1-1/2 in. IPS required:

$$\frac{25}{0.421} = 59 \text{ ft}$$

Fin side pressure drop determination:

$$d'_e = 0.43 \text{ in.}$$

$$D'_e = 0.0359 \text{ ft}$$

$$Re'_a = \frac{0.0359 \times 13,800}{0.0655}$$

$$= 7570$$

$$f = 0.0003$$

$$\Delta P = \frac{fG^2L_n}{5.22 \times 10^{10} D'_e S \phi_s}$$

L = length of exchanger, 59

n = number of passes, 1

$$S = \frac{\rho He}{\rho H_2O}$$

$$= \frac{0.69}{62.4}$$

$$= 0.011$$

ϕ_s = 1 for gases

$$\Delta P = \frac{3 \times 10^{-4}(1.38 \times 10^4)^2\ 59}{5.22 \times 10^{10} \times 3.59 \times 10^{-2} \times 1.1 \times 10^{-2}}$$

$$= 0.16 \text{ psi}$$

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