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PRESSURE-DROP-FLUID-FLOW CORRELATION FOR FIXED BEDS OF SMALL, IRREGULARLY SHAPED PARTICLES

M.J. Rosso Jr., G. STRICKLAND, AND J.S. MILAU

November 1976

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ABSTRACT

An equation, derived from experimental data, was developed to describe the pressure-drop-flow relationship in fixed beds of small, irregularly shaped particles. Within test limits the calculated and measured values agreed within 6%. Because this study was undertaken to solve a particular problem, it is specialized and the range of parameters is fairly restrictive.

All experimental runs were made with beds of particles with an average particle diameter ranging from 4.8 to 45 μm and hydrogen flow rates of 3.11×10^{-3} to 1.52×10^{-1} SCFM/in.². With one exception the bed material was deactivated FeTi hydride or unhydrided FeTi alloy; one run was made with SiC powder, which has approximately the same particle shape and surface characteristics as FeTi.

The pressure-drop data were used in the design of a hydride reservoir to determine the spacing of porous-metal tubes which serve as particle-barrier filters in the bed.

CONTENTS

ABSTRACT.....	iii
INTRODUCTION.....	1
Particle Attrition.....	1
Sub-Micron-Sized Particles.....	2
APPARATUS.....	2
EXPERIMENTAL PROCEDURE.....	3
RESULTS.....	4
EQUATION DEVELOPMENT.....	4
PROJECTIONS.....	14
CONCLUSIONS AND RECOMMENDATIONS.....	14
NOMENCLATURE.....	21
REFERENCES.....	21
APPENDIX A.....	21
APPENDIX B.....	23

TABLES

1. Materials used in experimental runs.....	3
2. Computer program used to compute constant K	5
3. Run 4, unhydrided FeTi alloy NL-2, average particle diameter 45 μm	10
4. Run 6, bed A-1-2, FeTi alloy NL-1 after 1710 cycles, average particle diameter 17.8 μm	10
5. Run 8, bed A-3-1, $\text{Fe}_{0.8}\text{TiMn}_{0.2}$ alloy INCO-1 after 207 cycles, average particle diameter 16.3 μm	11
6. Run 10, bed A-1, FeTi alloy VE-524 after 1200 cycles, average particle diameter 33.4 μm	11
7. Run 11, unhydrided FeTi alloy VE-525 <500 mesh, average particle diameter 17.2 μm	12
8. Run 12, bed A-1-2, FeTi alloy NL-1 <500 mesh, average particle diameter 16.5 μm	12
9. Run 15, SiC powder, average particle diameter 4.8 μm	13
10. Computer program used to compute pressure drop as a function of fluid-flow rate.....	13
11. Run to test dependence of pressure drop on average particle diameter.....	15
12. Run to test pressure-drop dependence on void-fraction change for a 5- μm average-particle-diameter bed.....	16
13. Run to test pressure-drop dependence on void-fraction change for a 10- μm average-particle-diameter bed.....	17
14. Run to test pressure-drop dependence on void-fraction change for a 15- μm average-particle-diameter bed.....	18
15. Optimized pressure-drop predictions as a function of particle size.....	19
16. Test of system sensitivity to void-fraction and particle-diameter change.....	20
A-1. Sample particle-size determination from sieve analysis.....	22

FIGURES

1. Predicted average particle size of bed as a function of long-term cycling	2
2. Experimental apparatus schematic	3
3. Run 4, pressure-drop-flow-rate measurements for unhydrided FeTi alloy NL-2.....	6
4. Run 6, pressure-drop-flow-rate measurements for bed A-1-2, FeTi alloy NL-1.....	7
5. Run 8, pressure-drop-flow-rate measurements for bed A-3-1, FeTi alloy INCO-1	7
6. Run 10, pressure-drop-flow-rate measurements for bed A-1, FeTi alloy VE-524.....	8
7. Run 11, pressure-drop-flow-rate measurements for unhydrided FeTi alloy VE-525.....	8
8. Run 12, pressure-drop-flow-rate measurements for bed A-1-2, FeTi alloy NL-1.....	9
9. Run 15, pressure-drop-flow-rate measurements for silicon carbide powder.....	9
10. Comparison of measured ΔP values with the computed ΔP values for all runs.....	14
11. Test of ΔP dependence on bed void fraction with average diameter.....	15
12. Test of ΔP dependence on bed void fraction with average particle diameter of 5 μm	16
13. Test of ΔP dependence on bed void fraction with average particle diameter of 10 μm	17
14. Test of ΔP dependence on bed void fraction with average particle diameter of 15 μm	18
15. Predicted average particle size as a function of long-term cycling.....	19
16. Test of system sensitivity to changes in void fraction and average particle diameter of bed	20

FIGURES

B-1A. Bed A-1, FeTi alloy VE-524, cycled 1200 times.....	23
B-1B. Same particle as in A.....	23
B-1C. Bed A-3-1, $\text{TiFe}_{0.8}\text{Mn}_{0.2}$ alloy INCO-1, cycled 207 times.....	23
B-1D. Bed H-1271, FeTi alloy VE-525, cycled 19,568 times in a laboratory apparatus	23
B-1E. Same particle as in D.....	24
B-1F. Same particle as in D and E.....	24
B-2A. Bed A-1-1, FeTi alloy NL-1, cycled 1439 times.....	24
B-2B. Portion of same field as in A.....	24
B-2C. Unhydrided FeTi alloy.....	25
B-2D. Same material as in C.....	25
B-2E. Silicon carbide powder, average size $4.8\ \mu\text{m}$	25
B-2F. Same material as in E.....	25
B-3. Comparison of a hydrided with an unhydrided FeTi alloy.....	26

PRESSURE-DROP-FLUID-FLOW CORRELATION FOR FIXED BEDS OF SMALL, IRREGULARLY SHAPED PARTICLES

INTRODUCTION

The storage of hydrogen in the form of a granular or powdered metal hydride is generally recognized as a safe and attractive technological method of storing energy.¹⁻³ The device for storing hydrogen as a metal hydride is commonly referred to as a hydride reservoir, which in simple terms consists of a pressure vessel filled with granular hydride and provided with a particle barrier, a gas connection, and a means of handling the thermal load encountered during hydriding and dehydriding.

The present work is related to the particle-barrier design, which must be suitable for the projected life of the storage system. Both the size of the porous-metal tubes (PMT) used as the particle barrier and the tube spacing must be considered in the design. The problem is complex because hydrides undergo gradual attrition or decrepitation during hydride-dehydride cycling,⁴ and the attrition rate is dependent upon such variables as the alloy composition and the geometric configuration of the containment vessel. The effects on the rate of attrition of the presence of a second phase in the alloy, the heat treatment of the alloy, and the charge-discharge rate are also under investigation.⁵

All the known decomposable hydrides having practicable hydrogen storage capacities expand volumetrically upon reacting with hydrogen (a process commonly referred to as hydriding or sorption), and they contract during the reverse reaction (dehydriding or desorption). The forward reaction can be considered a severe case of hydrogen embrittlement wherein microfissures develop, greatly increasing the surface area and, consequently, the reactivity and hydrogen storage capacity. Conditioning of the bed is required before a practical forward rate can be attained. This involves heating and evacuation in order to outgas the surface, and it is followed by flushing with hydrogen, which further cleans the hydride surface and initiates the embrittlement. This initial period is referred to as the activation step, during which an appreciable breakdown in particle size takes place. It is evident that the process of attrition is an inherent characteristic of the hydriding process,

and it has been shown to continue in test beds which are considered to be deep in relation to the container diameter. The local stresses in these deep beds cause fractures to occur at the activation-induced microfissures. The appreciable particle-to-particle and particle-to-wall friction limits the amount of movement relative to the free surface. As hydrogen is absorbed, the weakened particles attempt to accommodate themselves in the expanding bed and change their shapes by fracturing at the weakest points – the microfissures. This crunching and grinding action results in the rapid and progressive attrition of the bed material.

Because the pressure differential across the packed bed is a function of the average particle size, it is essential to have an accurate estimate of the particle size at the end of the projected reservoir lifetime. With this information, the number, size, and location of the PMT can be determined for a given pressure drop. Because of the high cost of the sintered porous-metal filter material which is used as the particle barrier, it is important to minimize the number and size of the elements used. From the experimental data obtained and the well-known relationships in the literature, an equation was developed for predicting the pressure drop in a bed of small, irregularly shaped particles of a limited size range.

Particle Attrition

During the activation of virgin bed material, it is characteristic for the granular bed material to form microfissures as the particles swell during the absorption of hydrogen (~15% for FeTi). The formation of these microfissures is essential and is the primary activation mechanism. The availability of many new surfaces for hydrogen absorption is extremely important because it appears that the initial hydriding of the alloy passivates the exposed surfaces and inhibits further penetration of the hydrogen into the alloy.⁵ This cracking results, therefore, in a much greater reactivity and storage capacity. The presence of these microfissures and the resultant weakness of the particles lead to decrepitation as the expanding particles seek accommodation in the interparticle spaces.

Particles that have been examined after hydriding are extremely fragile, and there is evidence that an appreciable amount of attrition takes place during the sieving operation for particle-size analysis. Typical microfissures caused by hydriding FeTi can be seen in Appendix B, Figures B-1A to B-1F, and a typical particle-size analysis can be found in Table A-1 in Appendix A.

Work is being performed by the International Nickel Company, on subcontract from BNL, to develop an alloy that will provide the required surface area and still exhibit the mechanical toughness to maintain its integrity.⁶

The attrition rate for all alloys seems to be extremely high for the first few hundred cycles, at which point it is greatly reduced and appears to be almost linear. Average particle diameters for bed A-1 were computed by using Eq. (7) below and measured pressure and fluid-flow values taken *in situ*. The resulting curve with extrapolation to the design bed life (4000 cycles) is presented in Figure 1. Very few data are available for the two other extrapolations presented on the same graph. The curves for beds A-1-2 and A-3-1 were developed by using the few points available from sieve analyses and by assuming that the curves would

have the same general shape as the curve for the A-1 bed.

The results look encouraging in terms of pressure drop as a function of long-term cycling. The average particle size predicted ($10\text{ }\mu\text{m}$) for the NL-2 material (bed A-1-2) will result in only a 2.0-psi pressure drop for each inch of bed material at the design flow rate of 1.73×10^{-2} standard cubic feet per minute per square inch (SCFM/in.²) or 2.49 standard cubic feet per minute per square foot (SCFM/ft²). Also it must be kept in mind that the data points used to generate the curve were taken from sieve analyses, during which additional attrition is known to take place. It is expected that the average particle size will be greater and, consequently, the pressure drop will be lower in the undisturbed bed of a working system.

Sub-Micron-Sized Particles

Appendix B shows the presence of sub-micron-sized particles (Figures B-2A and B-2B). The percentage of these particles observed in the alloy which had been subjected to the maximum number of cycles was small. Even after 4000 cycles our estimate is that they will represent $<1\%$ of the bed volume and, therefore, should not have a significant effect on the bed pressure drop unless they migrate into and plug the pores of the filter material. The escapement of even the smallest particles from the bed should not be appreciable because of the tortuous exit path presented by the sintered metal filter.

APPARATUS

All experimental measurements were made with glass tubes to facilitate the observation of the bed height. The apparatus consisted of a 200-ml and a 250-ml graduate which had been modified by adding a gas inlet and outlet, a coarse filter frit to support the bed, and a base to fit the Tap-Pak Volumeter. This device applies a preset number of taps to the base of the cylinder and is useful in producing various packing densities. One cylinder had an internal diameter of 1.22 in. (3.1 cm) and a cross-sectional area of 1.17 in.² (7.55 cm²); the other had a 0.827-in. (2.1-cm) i.d. and a 0.537-in.² (3.46-cm²) cross-sectional area.

The total system pressure differential was limited by the bursting strength of the glass cylinders and by the fact that the pressure was measured

Figure 1. Predicted average particle size of bed as a function of long-term cycling.

Figure 2. Experimental apparatus schematic.

with a mercury manometer having a range of only two atmospheres. The hydrogen flow rate was controlled by means of a micrometer needle valve, and it was measured with a Matheson mass flowmeter that had been calibrated against a Brooks flowmeter calibrator so that their readings differed by $<1\%$ of the scale reading. See Figure 2 for experimental apparatus schematic.

EXPERIMENTAL PROCEDURE

The sized bed material (see Table 1) was poured into the test cylinder and the cylinder was rolled to ensure that the bed was uniform and loosely packed. The bed's surface was leveled, the system was closed, the gas lines were connected, and the cylinder was attached to the pedestal of the Tap-Pak Volumeter. Hydrogen was flowed through

the bed in the down direction until all the air was purged out of the void spaces. A sudden drop in the ΔP measurement indicated when all the air had been displaced by hydrogen. The hydrogen flow rate was increased to the maximum attainable while keeping the bed pressure below 36 in. of mercury (Hg manometer limit). During this purging procedure the bed settled considerably. In some earlier runs the purging procedure was accomplished at low flow rates to avoid bed compaction. Data from these runs were discarded since the bed's void space was continuously changing during the course of the run.

Some earlier runs with fluid flow in the up direction indicated that the pressure drop across the bed was identical to values obtained for down flow until the threshold of incipient fluidization was reached. Since we were interested in the pressure-drop-flow relationship only for fixed beds, we elected to carry out all future experiments with down flow to avoid loosening the bed material.

When the final position of the bed was established, the void fraction was calculated from an accurate measurement of the bed height. The H_2 flow rate was carefully adjusted, and a suitable period of time was allowed for the system to come to equilibrium. Readings of the fluid-flow rate and pressure drop were recorded. The flow rate was gradually raised in increments of from 0.0035 SCFM/in.² (100 SCCM/in.²) to 0.0177 SCFM/in.² (500 SCCM/in.²) to the maximum attainable without exceeding the range of the manometer (36 in. Hg). Readings of pressure and flow rate were recorded at each step after satisfactory equilibrium was attained. The hydrogen flow was stopped and the bed was tapped a preset number of times or to a preselected void fraction by using

Table 1

Materials Used in Experimental Runs

Run	Bed ident.	No. of cycles	Alloy ident.	Alloy	Av. particle size, μm
4	N.A.	unhydrided	NL-2	FeTi	45.0
5	A-1-2	1710	NL-1	FeTi	17.8
6	A-1-2	1710	NL-1	FeTi	17.8
8	A-3-1	207	INCO-1	$\text{Fe}_{0.7}\text{TiMn}_{0.18}$	16.3
10	A-1	1200	VE-524	FeTi	33.4
11	N.A.	unhydrided	VE-525	FeTi	17.2
12	A-1-2	1710	NL-1	FeTi	16.5
15	N.A.	N.A.	N.A.	SiC	4.8

the Tap-Pak Volumeter. The flow of hydrogen was then resumed and another series of flow and pressure readings were noted and recorded.

RESULTS

It became apparent early in this study that the relationship between the fluid-flow rate and the bed pressure drop was not linear. A literature survey revealed that most studies concerned with beds of packed particles predicted a linear relationship in this laminar-flow region.⁷⁻¹² The work cited was done with beds of much larger particles and at much higher fluid-flow rates. In the present work, beds of particles $< 45 \mu\text{m}$ in size showed a definite deviation from linearity, and as the flow rate was raised, the rate of increase of the bed pressure was reduced.

A pressure-drop equation for the flow of fluid through a porous-metal wall was modified to describe the bed ΔP -fluid-flow relationship when it was found that the calculated values obtained by using this equation were in approximate agreement with the experimentally obtained values. An equation developed for Mott Metallurgical Co.¹³ by J. Baron at MIT approximated the curves we had obtained experimentally. The equation was developed to describe the pressure-drop data obtained at Mott by passing air through sintered porous-metal filter material, and it does not predict a linear flow-rate-pressure relationship. Baron speculated that, although the superficial velocity through the bed would indicate that it is in a region of laminar flow, some turbulence may be taking place in some of the smaller interstices between the particles. As the flow rate is increased, the character of the flow in an ever increasing number of passages is transformed from laminar to turbulentlike thus causing the ΔP -flow curve to deviate even further from linearity.¹⁴

EQUATION DEVELOPMENT

In an internal technical memo,¹⁵ J.A.F. Hill of MIT reported to Baron the development of an equation to predict ΔP across porous-metal filters as a function of fluid flow. The pressure-drop data were gathered by flowing air through a porous-metal sheet. He cites a paper by Green and Duwez¹⁶ as the source for this equation. We have found the root of the equation in publications by

Forscheimer¹⁷ in 1901 and by Reynolds¹⁸ in 1900. In the basic equation,

$$- \rho dp/dx = \alpha \mu G + \beta G^2, \quad (1)$$

the first (or α) term is the inertial resistance coefficient term, and is the dominant one at low fluid-flow rates. The second (or β) term is the viscous resistance coefficient term, and its contribution is negligible at low flow rates. As the flow rate increases, the contribution of the β term is significant, and it becomes dominant at very high flow rates. In this derivation α and β are determined experimentally. By rearranging the equation and using the equation of state for gas, $P = \rho RT$, we get

$$- P dp = \alpha \mu RT G \left(1 + \frac{\beta G}{\alpha \mu} \right) dx. \quad (2)$$

Integrating across the bed thickness t gives

$$P_u^2 - P_d^2 = 2 \alpha \mu RT G \left(1 + \frac{\beta G}{\alpha \mu} \right). \quad (3)$$

After suitable fitting to measured results the equation is presented as

$$\Delta P^2 = \alpha \mu RT \frac{\rho_s}{30} t \left(1 + \frac{\beta \rho_s}{60 \alpha \mu} Q \right) Q. \quad (4)$$

Note that the mass flow G has been replaced by $Q \rho_s / 60$, where Q is the superficial fluid velocity through the bed. The constant α should be a function of the system geometry and the characteristics of the bed material. The literature^{7,11,19} suggests that α should be proportional to $1/D_p^2$ and to $(1-\epsilon)^2/\epsilon^3$.

Starting with the assumption that

$$\alpha_c = K \left[\frac{(1-\epsilon)^2}{\epsilon^3} \frac{1}{D_p^2} \right], \quad (5)$$

we began to adjust the parameter relationships to cause the computed curve to fit the experimentally generated curve.

We were able to fit this relationship to our measured data by adjusting the exponent of the dimensionless void-fraction term and by adding a particle shape factor (Φ_s) and an empirically derived constant K . The value of the particle shape factor was chosen to be 0.67 after Carmen.⁸ A computer program was written (Table 2) to calculate the K value that best fitted the data for 14 runs. The constant K was computed and found to be 6.94×10^{-6} and to have the dimensional units of $\text{in.}/\mu\text{m}$. The maximum deviation of K for any

Table 2

Computer Program Used to Compute Constant K

```

5 REM THE CONSTANT 1.144E-6 IS A FUNCTION OF THE FLUID VISCOSITY
6 REM THE TEMPERATURE, THE GAS CONSTANT AND THE FLUID DENSITY STP
7 REM CONSTANT 1.144E-6 = (N*R*T*D)/30
10 PRINT "PROGRAM TO CALCULATE PRESSURE DIFFERENTIAL VALUES"
20 PRINT "IN A PACKED BED OF SMALL PARTICLES AS A FUNCTION"
30 PRINT "OF FLUID FLOW"
40 PRINT "WHICH PARAMETER DO YOU WANT TO FIND ??? K,D,A,P OR STOP"
50 PRINT "TYPE A 0 FOR K, 1 FOR D, 2 FOR A, 3 FOR P, 4 FOR STOP"
60 INPUT I
70 IF I<.5 THEN 120
80 IF I<1.5 THEN 260
90 IF I<2.5 THEN 340
100 IF I<3.5 THEN 400
110 IF I>3.5 THEN 450
120 PRINT "INPUT VOID FRACTION,V; PARTICLE DIA.,D; BD HEIGHT,T;"
125 PRINT "NUMBER OF DATA POINTS,N"
130 INPUT V,D,T,N
140 LET F=0
150 FOR J=1 TO N
160 PRINT "INPUT FLUID FLOW,Q; MEASURED PRESSURE,M;"
170 INPUT Q,M
180 LET K=((1-V).7)/((V1/3)*D*.67)
190 LET K=K*((T*1.14400E-06*Q)/((M*T+14.7)1/2-216.1))1.5
200 PRINT "K=";K
210 LET F=F+K
220 NEXT J
230 LET K=F/J
240 PRINT "AVERAGE K=";K
250 GO TO 50
260 PRINT "TO CALCULATE PARTICLE DIA."
262 PRINT "INPUT NO. DATA PTS,N; BED HT,T; VOID FRAC,V"\INPUT N,T,V
265 FOR J=1 TO N
270 PRINT "INPUT FLUID FLOW,Q; MEASURED PRESS.,M"\INPUT Q,M
280 LET K=6.94106E-06
290 LET A=((M*T+14.7)1/2-216.1)/(T*1.14400E-06*Q)
310 LET D=((1-V).7)/((V1/3)*K*SQR(A)*.67)
320 PRINT "PARTICLE DIA. IN MICRONS =" ;D
325 NEXT J
330 GO TO 50
340 PRINT "TO CALCULATE ALPHA INPUT VOID FRACTION,V; PARTICLE DIA.,D"
341 INPUT V,D
360 LET K=6.94106E-06
370 LET A=((1-V).7)/((V1/3)*K*D*.67)1/2
380 PRINT "ALPHA =" ;A
390 GO TO 50
400 PRINT "TO CALCULATE PRESS. DIFF. INPUT ALPHA,A; BED HT.,T"
401 PRINT "INPUT NUMBER OF DATA PTS,N"\INPUT A,T,N
405 FOR J=1 TO N
410 PRINT "INPUT Q"\INPUT Q
420 LET P=(SQR(A*T*1.14400E-06*Q+216.1)-14.7)/T
430 PRINT "PRESSURE DIFFERENTIAL IN PSI/IN=" ;P
435 NEXT J
440 GO TO 50
450 END

```

individual run from the average K value was $<2.3\%$.

We found that for our system α is best described by

$$\alpha_c = \left[\frac{(1-\epsilon)^{0.7}}{\epsilon^3 D_p K \Phi_s} \right]^2 \quad (6)$$

Expanding Eq. (4) we get

$$\Delta P^2 = \frac{\alpha_c \mu R T \rho_s t Q}{30} + \frac{\beta R T \rho_s Q^2 t}{1800} \quad (4A)$$

For the full range of the experimental parameters in this work the second, viscous resistance coefficient term is negligible. The following example is taken from Run 4, and it was chosen because it represents the case in which the β term makes its maximum impact on the ΔP value. Run 4 conditions are:

$$\begin{aligned} Q &= 1.40 \times 10^{-1} \text{ SCFM/in.}^2 \\ t &= 12.25 \text{ in.} \\ D_p &= 45 \mu\text{m} \\ \epsilon &= 0.518 \\ \beta &= 7.26 \times 10^4 \text{ in.}^{-1} \text{ (interpolated from Mott data}^{13}) \\ \alpha_c &= 4.2559 \times 10^8 \text{ in.}^{-2} \text{ computed} \end{aligned}$$

Substituting these values into Eq. (4A) and solving for ΔP gives $P = 17.43$ psi or 1.423 psi/in. if we accept the results of only the first term, and $P = 17.47$ psi or 1.426 psi/in. if we accept the results of both terms. Therefore, the maximum error introduced by ignoring the contribution of the viscous resistance term is $<0.2\%$ and is well within experimental error.

Dropping the second term reduces the equation to the general form

$$P_c t = (\alpha_c t \tau Q + P_a^2)^{1/2} - 14.7, \quad (7)$$

where

$$P_c = \Delta P / t = P_u - 14.7 / t \quad (8)$$

and

$$\tau = \mu \rho_s R T / 30. \quad (9)$$

By using Eqs. (7) to (9), the computed values (P_c) for each run were generated and compared with the measured values (P_m). The results are reported in Figures 3 to 9 and Tables 3 to 9. The computation was done with a PDP 11 Digital Equipment Corporation computer; the program is given in Table 10.

Figure 3. Run 4, pressure-drop-flow-rate measurements for unhydrided FeTi alloy NL-2 (35%) - 400 + 500; 65% - 270 + 400). Av. particle diameter 45 μm .

Figure 4. Run 6, pressure-drop-flow-rate measurements for bed A-1-2 which contained FeTi alloy NL-1 and had been cycled 1710 times. Av. particle diameter $17.8 \mu\text{m}$.

Figure 5. Run 8, pressure-drop-flow-rate measurements for bed A-3-1 which contained FeTi alloy INCO-1 and had been cycled 207 times. Av. particle diameter $16.3 \mu\text{m}$.

Figure 6. Run 10 pressure-drop-flow-rate measurements for bed A-1 which contained FeTi alloy VE-524 and had been cycled 1200 times. Av. particle diameter $33.4 \mu\text{m}$.

Figure 7. Run 11, pressure-drop-flow-rate measurements for unhydrided FeTi alloy VE-525 ($-500 + 10 \mu\text{m}$). Av. particle diameter $17.2 \mu\text{m}$.

Figure 8. Run 12, pressure-drop-flow-rate measurements for bed A-1-2 which contained FeTi alloy NL-1 ($-500 + 10 \mu\text{m}$) and had been cycled 1710 times. Av. particle diameter $16.5 \mu\text{m}$.

Figure 9. Run 15, pressure-drop-flow-rate measurements for silicon carbide powder ($<7 \mu\text{m}$ as purchased). Av. particle diameter $4.8 \mu\text{m}$.

Table 3

Run 4, Unhydrided FeTi Alloy NL-2,
Average Particle Diameter 45 μm

Fluid-flow rate		Void fraction: 0.518 Bed height: 12.25 in. Alpha: 4.25592×10^8	
SCFM/in. ²	SCCM/in. ²	P_m psi/in.	P_c psi/in.
3.11×10^{-3}	88.2	0.054	0.050
6.22×10^{-3}	176.3	0.100	0.099
9.33×10^{-3}	264.4	0.145	0.145
1.24×10^{-2}	352.5	0.190	0.190
1.56×10^{-2}	440.7	0.230	0.235
1.82×10^{-2}	515.6	0.255	0.270
2.43×10^{-2}	687.5	0.336	0.351
3.03×10^{-2}	859.3	0.414	0.426
4.25×10^{-2}	1203.1	0.558	0.568
6.07×10^{-2}	1718.6	0.750	0.762
7.28×10^{-2}	2062.4	0.876	0.881
9.10×10^{-2}	2578.0	1.05	1.05
1.03×10^{-1}	2921.7	1.15	1.15
1.21×10^{-1}	3437.3	1.31	1.30
1.40×10^{-1}	3952.9	1.45	1.45

Table 4

Run 6, Bed A-1-2, FeTi Alloy NL-1 After 1710 Cycles,
Average Particle Diameter 17.8 μm

Fluid-flow rate		Run: B Void fraction: 0.582 Bed height: 5.90 in. Alpha: 1.107644×10^9		C 0.550 5.50 in. 1.724300×10^9	
SCFM/in. ²	SCCM/in. ²	P_m psi/in.	P_c psi/in.	P_m psi/in.	P_c psi/in.
3.11×10^{-3}	88	0.142	0.130	0.210	0.201
6.22×10^{-3}	176	0.256	0.255	0.373	0.389
9.33×10^{-3}	264	0.365	0.374	0.536	0.565
1.24×10^{-2}	353	0.483	0.486	0.690	0.731
1.56×10^{-2}	441	0.588	0.599	0.841	0.895
3.03×10^{-2}	859	1.04	1.07	1.44	1.57
4.55×10^{-2}	1289	1.45	1.50	2.05	2.17
6.07×10^{-2}	1719	1.84	1.89	2.58	2.70
7.50×10^{-2}	2148	2.21	2.25	—	—
8.19×10^{-2}	2320	—	—	3.25	3.37
9.10×10^{-2}	2578	2.55	2.58		
1.12×10^{-1}	3179	3.00	3.01		

Table 5

Run 8, Bed A-3-1, Fe_{0.7}TiMn_{0.18} Alloy INCO-1 After 207 Cycles,
Average Particle Diameter 16.3 μm

		Run: <i>B</i>		<i>C</i>		<i>D</i>		<i>E</i>	
		Void fraction: 0.606		0.579		0.547		0.527	
		Bed height: 6.90 in.		6.45 in.		6.00 in.		5.75 in.	
		Alpha: 9.541468×10^8		1.376194×10^9		2.144716×10^9		2.849037×10^9	
Fluid-flow rate		P_m	P_c	P_m	P_c	P_m	P_c	P_m	P_c
SCFM/in. ²	SCCM/in. ²	psi/in.	psi/in.	psi/in.	psi/in.	psi/in.	psi/in.	psi/in.	psi/in.
3.11×10^{-3}	88	0.114	0.112	0.168	0.161	0.241	0.247	0.333	0.324
6.22×10^{-3}	176	0.212	0.219	0.335	0.311	0.462	0.473	0.606	0.615
9.33×10^{-3}	264	0.312	0.322	0.461	0.454	0.664	0.682	0.867	0.881
1.24×10^{-2}	353	0.406	0.419	0.605	0.587	0.863	0.877	1.12	1.13
1.56×10^{-2}	441	0.499	0.516	0.734	0.720	1.05	1.07	1.36	1.36
3.03×10^{-2}	859	0.883	0.923	1.27	1.27	1.77	1.84	2.30	2.31
4.55×10^{-2}	1289	1.26	1.29	1.80	1.76	2.49	2.51	3.14	3.13
5.76×10^{-2}	1633	-	-	-	-	3.00	2.98	-	-
6.07×10^{-2}	1719	1.59	1.63	2.26	2.19	-	-	-	-
7.58×10^{-2}	2148	1.90	1.93	2.69	2.59	-	-	-	-
9.10×10^{-2}	2578	2.20	2.22	-	-	-	-	-	-
1.06×10^{-1}	3008	2.48	2.48	-	-	-	-	-	-

Table 6

Run 10, Bed A-1, FeTi Alloy VE-524 After 1200 Cycles,
Average Particle Diameter 33.4 μm

		Run: <i>A</i>		<i>B</i>	
		Void fraction: 0.605		0.550	
		Bed height: 7.30 in.		6.40 in.	
		Alpha: 2.303256×10^8		4.897336×10^8	
Fluid-flow rate		P_m	P_c	P_m	P_c
SCFM/in. ²	SCCM/in. ²	psi/in.	psi/in.	psi/in.	psi/in.
3.11×10^{-3}	88	0.028	0.028	0.060	0.058
6.22×10^{-3}	176	0.057	0.055	0.112	0.116
9.33×10^{-3}	264	0.083	0.082	0.172	0.171
1.24×10^{-2}	352	0.113	0.108	0.227	0.225
1.56×10^{-2}	441	0.139	0.135	0.280	0.280
3.03×10^{-2}	859	0.268	0.255	0.507	0.518
4.55×10^{-2}	1289	0.390	0.373	0.737	0.745
6.07×10^{-2}	1719	0.498	0.485	0.952	0.956
7.58×10^{-2}	2148	0.608	0.592	1.15	1.15
9.10×10^{-2}	2578	0.717	0.695	1.34	1.34
1.06×10^{-1}	3008	0.814	0.793	1.54	1.52
1.21×10^{-1}	3437	0.926	0.887	1.71	1.68
1.37×10^{-1}	3867	1.02	0.985	1.89	1.86
1.52×10^{-1}	4297	1.12	1.07	2.05	2.01

Table 7

Run 11, Unhydrided FeTi Alloy VE-525 <500 Mesh,
Average Particle Diameter 17.2 μm

Fluid-flow rate		Run: A		B	
		Void fraction: 0.548 Bed height: 6.50 in. Alpha: 1.899263×10^8		0.523 6.35 in. 2.710130×10^9	
SCFM/in. ²	SCCM/in. ²	P_m psi/in.	P_c psi/in.	P_m psi/in.	P_c psi/in.
3.11×10^{-3}	88	0.206	0.219	0.311	0.307
6.22×10^{-3}	176	0.397	0.420	0.572	0.582
9.33×10^{-3}	264	0.567	0.607	0.804	0.833
1.24×10^{-2}	353	0.733	0.700	1.05	1.06
1.56×10^{-2}	441	0.894	0.951	1.27	1.29
2.28×10^{-2}	645	—	—	1.69	1.74
3.03×10^{-2}	859	1.53	1.64	2.17	2.17
3.79×10^{-2}	1074	—	—	2.57	2.57
4.25×10^{-2}	1203	—	—	2.83	2.79
4.55×10^{-2}	1289	2.14	2.24	—	—
6.07×10^{-2}	1719	2.69	2.78	—	—

Table 8

Run 12, Bed A-1-2, FeTi Alloy NL-1 <500 Mesh,
Average Particle Diameter 16.5 μm

Fluid-flow rate		Run: A		B		C	
		Void fraction: 0.559 Bed height: 5.65 in. Alpha: 1.769729×10^9		0.538 5.39 in. 2.376669×10^9		0.528 5.28 in. 2.740809×10^9	
SCFM/in. ²	SCCM/in. ²	P_m psi/in.	P_c psi/in.	P_m psi/in.	P_c psi/in.	P_m psi/in.	P_c psi/in.
3.42×10^{-3}	97	0.240	0.225	0.309	0.299	0.334	0.343
6.85×10^{-3}	194	0.450	0.435	0.547	0.573	0.649	0.653
1.03×10^{-2}	291	0.651	0.632	0.805	0.826	0.913	0.939
1.37×10^{-2}	388	0.840	0.815	1.04	1.06	1.16	1.20
1.71×10^{-2}	485	1.02	0.988	1.26	1.28	1.42	1.45
2.05×10^{-2}	582	1.18	1.15	1.46	1.49	1.66	1.68
2.74×10^{-2}	776	1.51	1.47	1.88	1.88	2.10	2.11
3.42×10^{-2}	970	1.82	1.76	2.26	2.24	2.49	2.51
4.01×10^{-2}	1135	2.02	1.99	2.49	2.53	2.81	2.83
4.67×10^{-2}	1324	2.26	2.24	2.86	2.84	3.16	3.17
5.34×10^{-2}	1513	2.53	2.49	3.14	3.13	—	—
6.01×10^{-2}	1703	2.81	2.72	—	—	—	—
6.68×10^{-2}	1892	3.03	2.94	—	—	—	—

Table 9

Run 15, SIC Powder, Average Particle Diameter 4.8 μm

Fluid-flow rate		Run: <i>B</i>		<i>C</i>		<i>D</i>	
		Void fraction: 0.692		0.663		0.622	
		Bed height: 2.76 in.		2.52 in.		2.24 in.	
		Alpha: 3.499501×10^9		5.155249×10^9		8.879637×10^9	
SCFM/in. ²	SCCM/in. ²	P_m psi/in.	P_c psi/in.	P_m psi/in.	P_c psi/in.	P_m psi/in.	P_c psi/in.
3.42×10^{-3}	97	0.463	0.448	0.593	0.649	1.09	1.09
6.85×10^{-3}	194	0.847	0.865	1.17	1.24	1.94	2.04
1.03×10^{-2}	291	1.24	1.26	1.73	1.79	2.81	2.91
1.37×10^{-2}	388	1.60	1.62	2.24	2.29	3.67	3.69
1.17×10^{-2}	485	1.96	1.97	2.75	2.77	4.45	4.41
2.05×10^{-2}	582	2.29	2.30	3.13	3.22	5.18	5.10
2.74×10^{-2}	776	2.96	2.93	4.03	4.07	6.58	6.37
3.42×10^{-2}	970	3.57	3.51	4.87	4.84	7.90	7.51
4.01×10^{-2}	1135	4.02	3.99	5.48	5.47		
4.67×10^{-2}	1324	4.54	4.49	6.19	6.13		
5.34×10^{-2}	1513	5.07	4.97	6.93	6.77		
6.01×10^{-2}	1703	5.60	5.44				
6.68×10^{-2}	1892	6.07	5.88				

Table 10

Computer Program Used to Compute Pressure Drop as a Function of Fluid-Flow Rate

```

10 REM-NOTATION- P=COMPUTED PRESSURE IN PSI/IN, T= BED HT. INCHES
20 REM M=VISCOSITY 1.559E-8 SLUGS/IN SEC, R=GAS CONST.2.4654E4
30 REM FT LB/SLUG DEG R, F=TEMP.DEG R (540 R), S= FLUID DENSITY
40 REM 1.616E-4 SLUGS/CU FT,H=SHAPE FCTR 0.67,V=VOID FRCTN
50 REM D=PARTICLE DIA MICRONS, Q=FLUID FLOW SCFM/SQ IN.
60 REM (M*R*F*S)/30 = 1.144E-6
70 PRINT "TO COMPUTE PRESSURE DIFFERENTIAL IN A PACKED BED OF SMALL"
75 PRINT "IRREGULARLY SHAPED PARTICLES AS A FUNCTION OF FLUID FLOW"
80 PRINT "RUN ? TYPE 1, STOP TYPE 2"\INPUT F
90 IF F>1.5 THEN 210
100 PRINT "INPUT VOID FRACTION V; PARTICLE DIA.,D; BED HT.,T;"
110 PRINT "NUMBER OF DATA PTS.,N"\INPUT V,D,T,N
120 LET D=D/25400\LET K=.1763
130 LET A=((((1-V)↑.7)/((V↑.3)*K*D*.67))↑.2
140 PRINT "ALPHA =" ;A
150 FOR I=1 TO N
160 PRINT "NEXT Q"\INPUT Q
170 LET P=((((A*T*1.14400E-06*Q)+216.1)↑.5)-14.7)/T
180 PRINT "P=" ;P
190 NEXT I
200 GO TO 80
210 END

```

PROJECTIONS

The equation, as derived, was found to agree with the experimental data within 6% (see Figure 10). This established its validity as a diagnostic tool. We were therefore able to predict pressure-drop values for systems that were difficult or impossible to duplicate with our experimental apparatus.

In the first computer projection the void fraction was held constant at 0.55, which, we feel, represents the densest packing obtainable in the bed of a working reservoir after 4000 cycles. The particle diameter was varied from 5 to 33.4 μm , and the predicted pressure-drop values are given in Table 11. The projected numbers for the 33.4- μm particle-diameter run can be compared directly with the measured values in Run 10B. These data were plotted for three flow rates and used to generate the curves presented in Figure 11.

A similar projection was made keeping the particle-diameter constant and changing the void fraction. The system's sensitivity to void-fraction change is demonstrated in Tables 12 to 14 and Figures 12 to 14. After review of the accumulated data, a conservative but realistic estimate of bed parameter levels was made.

A hydrogen reservoir with a bed 12 in. deep should have the following values at the conclusion of its 4000-cycle lifetime:

Figure 10. Comparison of measured ΔP values with the computed ΔP values for all runs.

(1) The average particle size should be $>10 \mu\text{m}$ but $<15 \mu\text{m}$.

(2) The void fraction should be >0.57 but <0.62 .

(3) The particle shape and surface roughness of hydrided FeTi powder should offer 50% more resistance to fluid flow than an equivalent-sized sphere ($\Phi_s = 0.67$).

With use of the above values, a second projection was made. The computer-generated values are tabulated in Table 15 and plotted in Figure 15. The system sensitivity to changing parameters is shown in Table 16 and Figure 16. This projection demonstrates that a small perturbation to the system makes a marked difference in the bed pressure drop. For example, if the ultimate average particle size at the end of the bed lifetime is 12 μm instead of 10 μm , the value of the bed ΔP would be $>25\%$ lower at the design flow rate. Should the void fraction be 0.60 instead of 0.57, it would be $>20\%$ lower.

On the basis of these results we feel that the highest curve presented in Figure 16 depicts a fairly reliable albeit conservative representation of expected bed pressure-drop values at 4000 cycles.

CONCLUSIONS AND RECOMMENDATIONS

The presented equation and its associated computer program are valuable tools that can be used to make reliable pressure-drop predictions for any system having similar geometries (fluid-flow rates, bed depth, particle size, and packing ratio).

In evaluating methods of reducing the problem of particle attrition, we found that alloy selection is the most important factor. Alloy VE-524, which was used in bed A-1, was found to be much superior in this respect to all other alloys tested. The microfissures necessary for maximum hydrogen storage capacity did appear; but the material seemed to possess the toughness necessary to maintain its integrity, even when at the bottom of an 11-in.-deep bed. Much time and effort have gone into investigating the nature of other alloys; but no other alloy has performed as well as VE-524, the first alloy tried. Our recommendation is that further attention be given to this alloy, and that it be considered a prime candidate for any anticipated future FeTi reservoirs.

Of the other factors that affect particle attrition, the bed depth appears to be extremely important.

Table 11

Run to Test Dependence of Pressure Drop on Average Particle Diameter
(Void fraction, 0.550; bed height, 6.40 in.)

Particle diameter: 5 μm Alpha: 2.185309×10^{10}		10 μm 5.463272×10^9	15 μm 2.428121×10^9	33.4 μm 4.897336×10^8		
Fluid-flow rate						
SCFM/in. ²	SCCM/in. ²	P_c psi/in.	P_c psi/in.	P_c psi/in.	P_m psi/in.	P_c psi/in.
3.11×10^{-3}	88	1.88	0.586	0.277	0.060	0.058
6.22×10^{-3}	176	3.14	1.07	0.527	0.112	0.116
9.33×10^{-3}	264	4.16	1.49	0.756	0.172	0.171
1.24×10^{-2}	353	5.03	1.87	0.967	0.227	0.225
1.56×10^{-2}	441	5.83	2.23	1.17	0.280	0.280
3.03×10^{-2}	859	8.81	3.60	1.99	0.507	0.518
4.55×10^{-2}	1289	11.22	4.75	2.70	0.737	0.745
6.07×10^{-2}	1719	13.26	5.73	3.32	0.952	0.956
7.58×10^{-2}	2148	15.05	6.60	3.88	1.15	1.15
9.10×10^{-2}	2578	16.68	7.40	4.39	1.34	1.34
1.06×10^{-1}	3008	18.17	8.13	4.86	1.54	1.52
1.21×10^{-1}	3437	19.55	8.81	5.30	1.71	1.68
1.37×10^{-1}	3867	20.93	9.49	5.74	1.89	1.86
1.52×10^{-1}	4297	22.16	10.09	6.14	2.05	2.01

Figure 11. Test of ΔP dependence on bed void fraction with average particle diameter.

Table 12

Run to Test Pressure-Drop Dependence on Void-Fraction Change
for a 5- μm Average-Particle-Diameter Bed

Fluid-flow rate		Void fraction: 0.500 Alpha: 4.486725×10^{10}	0.600 1.099431×10^{10}	0.650 5.641656×10^9	0.700 2.914560×10^9
SCFM/in. ²	SCCM/in. ²	P_c psi/in.	P_c psi/in.	P_c psi/in.	P_c psi/in.
3.42×10^{-3}	97	5.08	1.40	0.732	0.383
6.85×10^{-3}	194	9.11	2.68	1.43	0.757
1.03×10^{-2}	291	12.58	3.89	2.11	1.12
1.37×10^{-2}	388	15.60	5.00	2.75	1.48
1.71×10^{-2}	485	18.35	6.06	3.36	1.82
2.05×10^{-2}	582	20.89	7.06	3.96	2.16
2.71×10^{-2}	776		8.97	5.12	2.83
3.42×10^{-2}	970		10.71	6.19	3.48
4.01×10^{-2}	1135		12.13	7.08	4.00
4.67×10^{-2}	1324		13.63	8.04	4.58
5.34×10^{-2}	1513			8.97	5.15
6.01×10^{-2}	1703			9.06	5.70

Figure 12. Test of ΔP dependence on bed void fraction with average particle diameter of 5 μm .

Table 13

Run to Test Pressure-Drop Dependence on Void-Fraction Change
for a 10- μ m Average-Particle-Diameter Bed

Fluid-flow rate		Void fraction: 0.500 Alpha: 1.121681×10^{10}	0.600 2.748577×10^9	0.650 1.410414×10^9	0.700 7.286399×10^8
SCFM/in. ²	SCCM/in. ²	P_c psi/in.	P_c psi/in.	P_c psi/in.	P_c psi/in.
3.42×10^{-3}	97	1.42	0.361	0.187	0.097
6.85×10^{-3}	194	2.73	0.715	0.371	0.193
1.03×10^{-2}	291	3.96	1.06	0.554	0.289
1.37×10^{-2}	388	5.09	1.40	0.733	0.383
1.71×10^{-2}	485	6.16	1.73	0.909	0.477
2.05×10^{-2}	582	7.18	2.05	1.08	0.570
2.74×10^{-2}	776	9.12	2.68	1.43	0.757
3.42×10^{-2}	970	10.88	3.29	1.77	0.939
4.01×10^{-2}	1135	12.32	3.79	2.05	1.09
4.67×10^{-2}	1324	13.84	4.35	2.37	1.27
5.34×10^{-2}	1513		4.89	2.69	1.44
6.01×10^{-2}	1703		5.42	2.99	1.61

Figure 13. Test of ΔP dependence on bed void fraction with average particle diameter of 10 μ m.

Table 14

Run to Test Pressure-Drop Dependence on Void Fraction Change
for a 15- μm Average-Particle-Diameter Bed

Fluid-flow rate		Void fraction: 0.500 Alpha: 4.985250×10^9	0.600 1.221590×10^9	0.650 6.268506×10^8	0.700 3.238400×10^8
SCFM/in. ²	SCCM/in. ²	P_c psi/in.	P_c psi/in.	P_c psi/in.	P_c psi/in.
3.42×10^{-3}	97	0.648	0.162	0.083	0.043
6.85×10^{-3}	194	1.27	0.322	0.166	0.086
1.03×10^{-2}	291	1.88	0.481	0.249	0.129
1.37×10^{-2}	388	2.45	0.637	0.330	0.172
1.71×10^{-2}	485	3.01	0.791	0.411	0.214
2.05×10^{-2}	582	3.54	0.943	0.490	0.256
2.74×10^{-2}	776	4.59	1.25	0.653	0.341
3.42×10^{-2}	970	5.57	1.54	0.811	0.424
4.01×10^{-2}	1135	6.38	1.79	0.947	0.497
4.67×10^{-2}	1324	7.26	2.07	1.10	0.577
5.34×10^{-2}	1513	8.11	2.35	1.25	0.658
6.01×10^{-2}	1703	8.93	2.62	1.40	0.738

Figure 14. Test of ΔP dependence on bed void fraction with average particle diameter of 15 μm .

Table 15

Optimized Pressure-Drop Predictions as a Function of Particle Size
(Void fraction, 0.57; bed height, 5.58 in.)

Particle diameter: 5 μm 10 μm 15 μm 20 μm 30 μm 40 μm			Alpha: 1.65455×10^{10} 4.13638×10^9 1.83839×10^9 1.03409×10^9 4.59597×10^8 2.58524×10^8					
Fluid-flow rate			P_c	P_c	P_c	P_c	P_c	P_c
SCFM/in. ²	SCFM/ft ²	SCCM/in. ²	psi/in.	psi/in.	psi/in.	psi/in.	psi/in.	psi/in.
6.94×10^{-3}	1.00	196.6	2.89	0.947	0.457	0.266	0.121	0.069
1.73×10^{-2}	2.49	489.6	5.47	2.01	1.03	0.623	0.293	0.169
3.47×10^{-2}	5.00	983.2	8.53	3.40	1.84	1.15	0.561	0.329
8.33×10^{-2}	12.00	2359.8	14.38	6.17	3.56	2.33	1.21	0.735

Figure 15. Predicted average particle size as a function of long-term cycling.

During the charging cycle, FeTi increases its volume 15% when hydrogen is absorbed. As a particle trapped near the bottom of the bed begins to expand, it is unable to lift the weight of the bed above it. The particle, already weakened by many microfissures or cracks, is fitted into the bed by crumbling into a few smaller particles. As this process is repeated a few hundred times, the average particle size of the bed becomes very small.

The attrition rate slows down as the particles approach a size that can be accommodated during the hydrogen charging cycle. Possibly by limiting the bed depth to six inches, or preferably even less, the attrition or decrepitation problem may be greatly alleviated.

Our computer predictions indicate that in a reservoir designed to store off-peak electric power in the form of hydrogen, where the hydrogen flow

Table 16

Test of System Sensitivity to Void-Fraction and Particle-Diameter Change

(Bed height, 5.58 in.)

Fluid-flow rate			Particle diameter: 10 μm Void fraction: 0.57 Alpha: 4.1364×10^9	10 μm 0.60 2.7486×10^9	12 μm 0.57 2.8733×10^9
SCFM/in. ²	SCCM	SCCM/in. ²	P_c psi/in.	P_c psi/in.	P_c psi/in.
3.11×10^{-3}	100	88	0.460	0.314	0.327
6.22×10^{-3}	200	176	0.861	0.597	0.622
9.33×10^{-3}	300	264	1.22	0.858	0.892
1.24×10^{-2}	400	353	1.54	1.10	1.14
1.56×10^{-2}	500	441	1.86	1.33	1.38
1.73×10^{-2}	556	491	2.01	1.45	1.50
3.03×10^{-2}	1000	859	3.08	2.27	2.34
4.55×10^{-2}	1500	1289	4.11	3.07	3.17
6.07×10^{-2}	2000	1719	5.01	3.78	3.90
7.58×10^{-2}	2500	2148	5.80	4.41	4.55
9.10×10^{-2}	3000	2578	6.54	4.99	5.15
1.06×10^{-1}	3500	3008	7.21	5.53	5.69
1.21×10^{-1}	4000	3437	7.83	6.03	6.21
1.37×10^{-1}	4500	3867	8.46	6.54	6.73
1.52×10^{-1}	5000	4297	9.02	6.99	7.19

Figure 16. Test of system sensitivity to changes in void fraction and average particle diameter of bed.

rates are low ($<1.73 \times 10^{-2}$ SCFM/in.²), the filter tubes should be placed no further apart than 10 in. For automotive application, where the hydrogen flow rates are much higher ($>1.73 \times 10^{-1}$ SCFM/in.²), the filter tubes should be placed no further apart than 4 in.

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NOMENCLATURE

D_p	average particle diameter, μm
K	experimentally determined constant, $6.94 \times 10^{-6} \text{ in.}/\mu\text{m}$
G	fluid mass flow, slugs/min
P	pressure, psi
$P_c = \Delta P/\text{in.}$	computed pressure differential, psi/in.
P_d	pressure downstream, psi
P_u	pressure upstream, psi
Q	fluid flow, SCFM/in. ²
R	gas constant, $2.4654 \times 10^4 \text{ ft-lb/slug-}^\circ\text{R}$
t	filter thickness or bed height, in.
T	temperature (absolute), $^\circ\text{R}$
α	experimentally determined constant, in. ⁻²
α_c	computed constant, in. ⁻²
β	experimentally determined constant, in. ⁻¹
$\epsilon = V - \text{void fraction}$	dimensionless
μ	fluid viscosity, slugs/in.-sec
Φ_s	particle shape factor, dimensionless
ρ	fluid density, slugs/ft ³
ρ_s	fluid density at STP, slugs/ft ³
ΔP	($P_u - P_d$) bed pressure drop
τ	constant for this test system

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APPENDIX A

The average particle diameter for each bed was determined by sieve analysis of the material larger

Table A-1
Sample Particle-Size Determination From Sieve Analysis (Run 10 Material)

Sieve size, ASTM gauge	d_{pi} , Microns	x_i , Fraction	
-20 + 50	575	0.0027	0.000005
-50 + 60	275	0.0191	0.000069
-60 + 80	215	0.0448	0.000208
-80 + 100	165	0.0656	0.000398
-100 + 140	128	0.1022	0.000798
-140 + 170	98	0.0464	0.000473
-170 + 200	82.5	0.0850	0.001030
-200 + 270	64	0.1011	0.001580
-270 + 400	45.5	0.2077	0.004565
-400 + 500	31.7	0.1175	0.003706
-500 + 10 μm	16*	0.1844	0.011525
- 10 μm	4.2*	0.0235	0.005595
			$\sum_i (x_i/d_{pi}) = 0.029952$

$$D_p = \frac{1}{\sum_i (x_i/d_{pi})} = 33.4 \mu\text{m}$$

*Estimated values.

than 25.4 μm (500 mesh). The size of the portion of the bed material that was smaller than 500 mesh was estimated on the basis of photographs taken with a scanning electron microscope (SEM). The average value for each sieve size range and the fraction of each range were used in the following formula, which is taken from Perry's *Handbook of Engineering Fundamentals*:

$$D_p = \frac{1}{\sum_i (x_i/d_{pi})},$$

where

x_i = fraction of material in a sieve size range,
 d_{pi} = algebraic average particle size in that range.

Two checks were made on the values obtained. Measured bed pressure values were used in conjunction with the computer program listed in Table 2 to compute the average particle size in the bed. The computed value was used as an aid in estimating the average diameter to be used for the sub-sieve-sized portion of the bed. In every case the computed values indicated that these fine particles had an average particle diameter reasonably close to the estimated value.

In the second check, six samples were sent for particle-size analysis to the Majac Division of

Donaldson Company in Tulsa, Oklahoma. The technologist who made the measurements, using a Coulter Counter, noticed an appreciable amount of particle attrition during the analysis procedure, which she attributed to the stirring necessary to keep the powder suspended in the electrolyte solution. The results obtained were generally 30% lower than our measurements (Table A-1). The speculation that the discrepancy is a result of particle deaggregation during the analysis is reinforced by the fact that their measurement of the Run 10 (bed A-1, alloy VE-524) material is only 19% lower than our value. This particular alloy has demonstrated a definite resistance to attrition in our engineering-scale cycling runs. One sample (H-1271) had been cycled 19,568 times in a laboratory-scale apparatus. This material did not, from a cursory examination, seem to break down as much. In fact, its average particle size was still $>100 \mu\text{m}$ when a sieve analysis was done at 5000 cycles, which we attribute to its having been cycled with a very shallow bed depth. The analysis of this material made by Majac indicated that the average particle size was 5.7 μm . Appendix B, Figures B-1D, E, and F, are SEM photographs of this material, and they demonstrate its fragile nature.

APPENDIX B

The following photomicrographs were taken with a scanning electron microscope.

Figure B-1A. Bed A-1, FeTi alloy VE-524, cycled 1200 times. Shows typical microfissures resulting from hydride-dehydride cycling. Although the particle exhibits a substantial amount of cracking, this alloy has demonstrated its ability to maintain its integrity with a minimum number of small particles spalling off (500 $\times$).

Figure B-1B. Same particle as in A. Arrow indicates a 2- μ m particle. The average particle size for this bed was 33.4 μ m (1000 $\times$).

Figure B-1C. Bed A-3-1, Fe_{0.7}TiMn_{0.18} alloy INCO-1, cycled 207 times. A typical particle showing cracking equivalent to that of the alloy in A and B even though it had been cycled many times less. The average particle size for this bed was 16.3 μ m (1000 $\times$).

Figure B-1D. Bed H-1271, FeTi alloy VE-525, cycled 19,568 times in a laboratory apparatus. Shows one large particle with much small debris in the background that has spalled off the larger particles. This bed had an average particle size of 5.7 μ m (200 $\times$).

Figure B-1E. Same particle as in D (500 $\times$).

Figure B-1F. Same particle as in D and E. Shows extensive cracking and illustrates the extreme fragility of this material. Although the bed appeared to be composed of fairly large-sized particles, a measurement with a Coulter Counter particle-size analyzer indicated that its average particle size was 5.7 μm . The large particles obviously broke up from contact with the blades of the stirrer used in this technique to keep the powder dispersed in the electrolyte. Comparing its reaction with that of other alloys that received the same treatment, we conclude that this alloy would have had an attrition rate similar to that of our other alloys if it had been run on an engineering scale deep bed rather than on a laboratory scale shallow bed (1000 $\times$).

Figure B-2A. Bed A-1-1, FeTi alloy NL-1, cycled 1439 times. Typical particle-size distribution (2000 $\times$).

Figure B-2B. Portion of same field as in A. Sub-micron-sized particles are few (10000 $\times$).

Figure B-2C. Unhydrided FeTi alloy. Note the absence of cracking and also the sharp edges and smooth fracture faces (500 $\times$).

Figure B-2D. Same material as in C (500 $\times$).

Figure B-2E. Silicon carbide powder, average particle size 4.8 μm . This material was used in Run 15 (5000 $\times$).

Figure B-2F. Same material as in E. Note the similarity in particle shape and size distribution to that in C and D (1000 $\times$).

Figure B-3A and 3B. Comparison of a hydrided (top) with an unhydrided (bottom) FeTi alloy (500 $\times$).