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FROM THERMOCHEMICAL WATER-SPLITTING CYCLES

by

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EQUILIBRIUM EFFECTS IN HIGH-PRESSURE HYDROGEN PRODUCTION
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ABSTRACT

When hydrogen comes into widespread use as a supplemental fuel, a chemical feedstock, and a primary, future energy carrier, it must be available at pressures of the order of 50 atmospheres. Existing studies of hydrogen transmission indicate that pipeline pressures of 50 to 100 atmospheres will yield an energy carrier system with better cost-effectiveness than underground transmission of electricity. Because high capacity hydrogen compressors have a low compression ratio, high supply pressures are required. This requirement will affect product separations steps and process heat load-line matching.

The hydrogen production steps of a large number of projected water-splitting cycles were classified according to whether the sum of the mole numbers of gaseous products is larger or smaller than the sum of the mole numbers of gaseous reactants. When product mole numbers are larger, the hydrogen production step occurs at relatively high temperatures (about 600°C or higher). When reactant mole numbers are larger, the required temperature is generally low (about 300°C or lower). There were few exceptions, though some water-splitting cycles based on organic chemical reactions fit into a temperature range between these two categories. A group of generalized relationships are presented for hydrogen production steps such that ΔG, the Gibb's free energy change for the reaction, is zero. For equilibria favored by, and not favored by pressure, a series of relationships between the hydrogen mole fraction and product pressure can be defined. The trade-offs between product stream composition and input heat temperature can be assessed. The degree to which feed stream impurities can be tolerated, given fixed operating variables, can also be determined.

INTRODUCTION

As fossil fuel resources are consumed, we struggle with the problem of finding a major energy source for the future.[1] There is at present a strong tendency to permit coal to assume the leading role as a future energy resource, [2,3] but it, too, is finite.[4] An increased dependence on coal will be accompanied by increased environmental problems in the form of volatile and acid oxides. The problems created by increased injection of oxides of carbon [5] and sulfur [6] into the atmosphere are

poorly defined, but most investigators assume that any sharp increase in atmospheric levels of CO_2 or SO_2 is damaging.[5,7,8]

When oil, natural gas, and coal are depleted, a means to provide power for future societies must be available. Today, hydrogen appears to be the most promising long-range answer to the difficult questions raised by the depletion of our fossil-fuel resources. As a gaseous carrier, it lends itself to efficient pipeline transmission and distribution, and as a fuel, it is very clean; it returns to the environment as water.[9,10]

The problems to be solved in conversion to this energy scenario are: 1) how to distribute the energy over long distances and 2) the best form of transmission. Our experience with the central station generator, fueled by natural gas from sources hundreds of miles distant, can answer the first question. Consideration of our environment and the roles played by hydrogen and water answer the second.[9]

The energy will be transmitted and distributed by pipelines, which offer the most cost-effective means of moving energy from place to place.[11] The source of this energy will be nuclear fission, nuclear fusion, or solar concentration. The form of energy to be distributed in this scenario will be high-pressure hydrogen, made by an advanced hydrogen production technology such as thermochemical water-splitting.[12]

Research in thermochemical water-splitting technologies has indicated that hydrogen production plants will be quite large — perhaps as large as present-day petroleum refineries. This fact alone makes it appear certain that fuel production centers must be distant from end-use locations.[13] The trend away from local energy distribution, in any form, has strengthened during the last 2 or 3 decades. Previously, power stations were near the location of their consumers, but by the 1960's, it had become very difficult to site nonfossil generating systems near population centers. It is still possible to place a natural-gas-fired central station, such as Manhattan's Waterside Station (900 MW_e),[14] near a dense population center, but large coal-fired generation centers such as western Pennsylvania's Conemaugh Station (1700 MW_e), [14] are most effectively sited at the fuel source. A hydrogen transmission and distribution system would permit consumer-scale energy distribution as electricity from close-in fuel cell central stations, and allow gas consumers (non-electricity users) to benefit from the economies in the distant placement of large energy complexes with pipeline transmission of gaseous hydrogen.

As natural gas is at present, hydrogen will be a more attractive form of distributed "fuel" than electricity. It can be burned directly for heat or used to generate electricity at higher efficiencies than are currently possible by state-of-the-art, heat-shaftpower generators. Pipeline energy distribution as pressurized hydrogen will be almost insensitive to "peaking," and the established global networks of transmission and distribution centers and gas storage reservoirs should be directly usable with hydrogen.

THERMOCHEMICAL WATER-SPLITTING: LABORATORY PROVED

Thermochemical water-splitting is a laboratory-proved concept and provides a method for converting heat energy to a chemical fuel without reliance on electricity generation. At Los Alamos Scientific Laboratories [15] and at the EURATOM Laboratory at Ispra, Italy, several chemical sequences have been operated with recycled materials to produce hydrogen and oxygen.[16] In the American Gas Association (A.G.A.) thermochemical hydrogen program at IGT, several cycles have been demonstrated in the laboratory using recycled materials.[17] Engineering analyses of promising cycles based on a combination of electrochemical and thermochemical steps show that plant energy efficiencies could be as high as 45%.[18,19]

Successful, large-scale thermochemical production of clean hydrogen promises to alleviate a large number of acute problems we now face in energy and fuel distribution and transmission.

THE PENALTY FOR HYDROGEN COMPRESSION

Transmission and distribution of hydrogen by pipelines can be compared with natural gas and electricity transmission. On an energy-delivered basis, natural gas will be the cheapest of the three to transmit; hydrogen will be intermediate in cost; and electricity will be the most expensive.[20,21] Because of the lower (volumetric) heating value of hydrogen (325 Btu/ft^3) compared with that of natural gas (1050 Btu/ft^3), three times as much hydrogen must be transported to achieve an equivalent energy delivery rate.

In various parts of the world, hydrogen is transmitted by pipeline. Compared with natural gas transmission, the distances are relatively short and the energy deliveries are small. Because of economic and technical factors, the long-distance transmission of hydrogen will require the use of new, high-capacity compressors. These compressors must be designed to be able to resist the high diffusivity of hydrogen. Their subsequent tendency to leak may cause compressor-casing and valve-sealing problems not found with natural gas.

Hydrogen-transmission pipelines are expected to operate at pressures between 50 and 140 atm. Hydrogen not manufactured at high pressure will require an initial compression step to raise the gas to the pipeline entry pressure of 50 atm, or higher. Natural gas transmission lines, generally operated at ~50 atm (750 psia), can be matched in energy delivery capacity by hydrogen lines only by transmission at much higher pressure (100 atm) or in pipelines of greater throughput.

Hydrogen, unlike heavier gases, has a very low compressibility at ordinary pressures; consequently, in order to supply it to high-pressure transmission lines, a substantial amount of work is required. Using Scheel's correlation to calculate the fuel requirement for radial turbo-compression,[22] we have obtained the simple fuel requirements for compressing hydrogen from atmospheric pressure (14.7 psia) to 69 atm (1014.7 psia). We then calculated the

fuel requirement for compression from 30 atm (441 psia) to the same upper pressure, 69 atm. The data are summarized in Table 1. The calculations were based on the assumption of no changes in compressibility over the range of compression (dz=0), a fuel factor of unity, and a polytropic efficiency of 94.6%. It was also assumed that 1.4 was the highest pressure ratio available using radial turbo-compressors.

The character of the hydrogen work equivalent for compression is shown in Figure 1, which indicates the hydrogen work fraction for compression to 100 atm as a function of the compression ratio (100 atm/P_{in}) for several heat-to-work efficiencies. What is clear is that small increases in delivery pressure of H_2 are well repaid by rapidly decreasing fuel requirements for raising the hydrogen product to transmission pressures. What is most dramatically indicated in Figure 1 is the value to be gained by primary hydrogen delivery at pressures as low as 10 atm.

HYDROGEN PRODUCTION STEPS

Forty-seven hydrogen production steps from thermochemical water-splitting cycles were analyzed. The analytical formalism used is that of Aris.[23] Of all the cycles studied, 19 belong to a trivial class such that pressure plays no role in constraining equilibrium ratios, and 4 have no gaseous reactants, so that the equilibrium pressure of products depends only on system pressure and product stoichiometry.

Classifying Reactions

A chemical reaction can be written as the sum of all species, A_i, and their stoichiometric coefficients, α_i

$$\alpha_1 A_1 + \alpha_2 A_2 + \dots + \alpha_n A_n \equiv 0. \tag{1}$$

In this scheme $\alpha_i > 0$ for products and $\alpha_i < 0$ for reactants, and the number of moles of A_i present at any time, N_i, is given by $N_i = N_{io} + \alpha_i X$, where N_{io} is the number of moles of A_i present initially, and X is the extent of reaction. The value of X is given by $(N_i - N_{io})/\alpha_i$. For simplicity we assume there are no products present initially, so that X = 1 when 1 mole of H_2 is present at equilibrium, and $N_i = \alpha_i$ for products. Further, it was assumed that reactants were initially present in stoichiometric proportions.

-4-

Table 1. HYDROGEN WORK EQUIVALENTS FOR GAS COMPRESSION

$C_p/C_v = 1.41$; $\eta_w = 0.333$; Capacity = 1000 ft^3/min

Inlet Pressure (atm)	Pressure Ratio	No. Stages	Hp	"f(H$_2$)"
1 (14.7 psia)	1.4	13	302	0.118
	1.3	17	298	0.117
	1.2	24	295	0.115
30 (441 psia)	1.4	3	59	0.0232
	1.3	4	59	0.0231
	1.2	5	58	0.0226
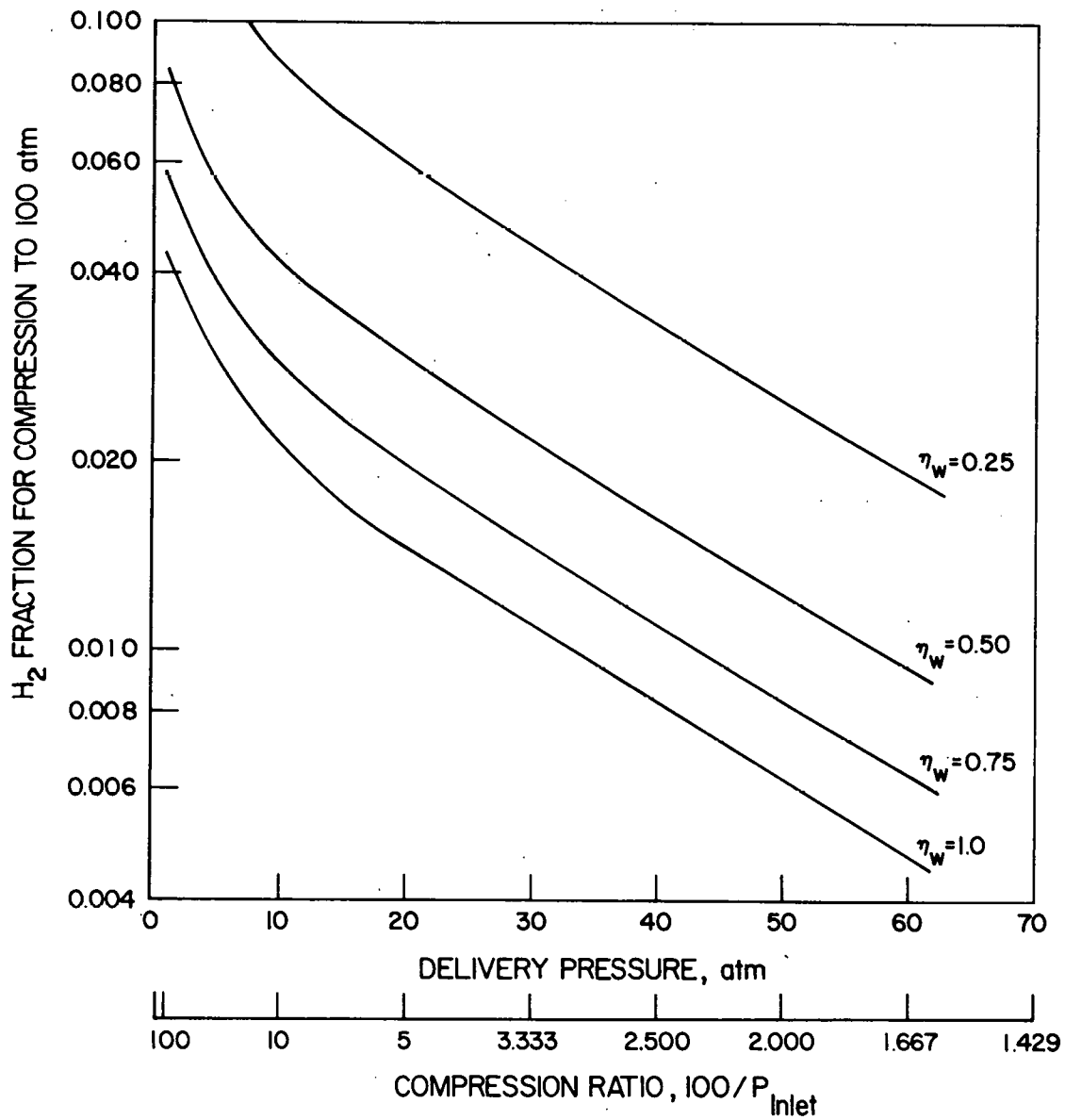
Figure 1. THE HYDROGEN FRACTION FOR COMPRESSION TO 100 atm.
(dz = 0, C_p/C_v = 1.41, fuel factor = 1.0, η_p = 0.946,
V = 1000 SCF/min)

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In this way, after calculating the number of moles of one reactant at equilibrium, we can find the amounts of other reactants from —

$$N_j = \alpha_j(N_{io}/\alpha_i + 1) \tag{2}$$

The Gibbs free energy change, ΔG, can be used to calculate the equilibrium composition,

$$K_p \equiv \exp(-\Delta G/RT) = \prod_{i=1}^{n} p_i^{\alpha_i} \tag{3}$$

where the p_i are the partial pressures of <u>gaseous</u> species A_i and n represents the number of the <u>gaseous</u> species involved in the reaction (i > n for solids and liquids). We assume these do not affect equilibrium.

For any reaction, we have all the α_i, K_p, and the total equilibrium pressure P. By defining $\overline{\alpha} \equiv \sum_{i=1}^{n} \alpha_i$, and letting n be the total number of moles of the gaseous species at equilibrium we can rewrite Equation 3 as a natural function of $\overline{\alpha}$, N, and P. Let there be k − 1 gaseous products (k ≥ 2), so that for i ≤ (k − 1), $N_i = \alpha_i$ and $N_j = \alpha_j[(N_{ko}/\alpha_k) + 1]$ for j ≥ k. The total number of moles of gaseous species can be calculated as a function of $\overline{\alpha}$, as can the partial pressures, $p_i = [\alpha_i/N(\overline{\alpha})]P$ for i ≤ (k − 1), and $p_i = \alpha_i[(N_{ko}/\alpha_k) + 1][P/N(\overline{\alpha})]$ for i ≥ k.

From these we generate an algorithm for K_p in terms of P, N, $\overline{\alpha}$, α_i and α_j,

$$K_p = P^{\overline{\alpha}} N^{-\overline{\alpha}} \prod_{i=1}^{n} \alpha_i^{\alpha_i} \prod_{j=k}^{n} [(N_{ko}/\alpha_k) + 1]^{\alpha_j} \tag{4}$$

and all the useful parameters are reduced to functions of the stoichiometric coefficients, $\overline{\alpha}$, $\sum_{i=k}^{n} \alpha_i$ and $\prod_{i=1}^{n} \alpha_i^{\alpha_i}$.

While the potential number of combinations of α_i and permutations of the derived parameters is virtually unlimited, it has been found adequate for our purposes here to classify the reactions studied according to 2 parameters, $\bar{\alpha}$, the sum of stoichiometric coefficients and R, defined by —

$$R \equiv \sum_{i=1}^{k-1} \alpha_i \Big/ \sum_{i=k}^{n} \alpha_i \qquad (5)$$

or simply

$$R = \left(\bar{\alpha} \Big/ \sum_{i=k}^{n} \alpha_i\right) - 1 \qquad (6)$$

In the Appendix, the hydrogen production reactions are listed according to their $(\bar{\alpha}, R)$ class. •

PRESSURE EFFECTS — DISCUSSION

The algorithm defined previously was used to calculate the equilibrium mole fractions of hydrogen, $\chi(H_2)$, as a function of total pressure P, for the hydrogen production steps of 47 thermochemical water-splitting cycles that have been studied or assessed at IGT. Ten non-trivial classes of reactions resulted, and these have been analyzed to produce a typical $\chi(H_2)$ vs. P plot, for the case $\Delta G = 0$ ($K_p = 1$). The plotted relationships, paradigms for the separate sets of reactions, are shown in Figure 2. The hydrogen production steps are listed in the Appendix.

Reactions Not Favored by Pressure

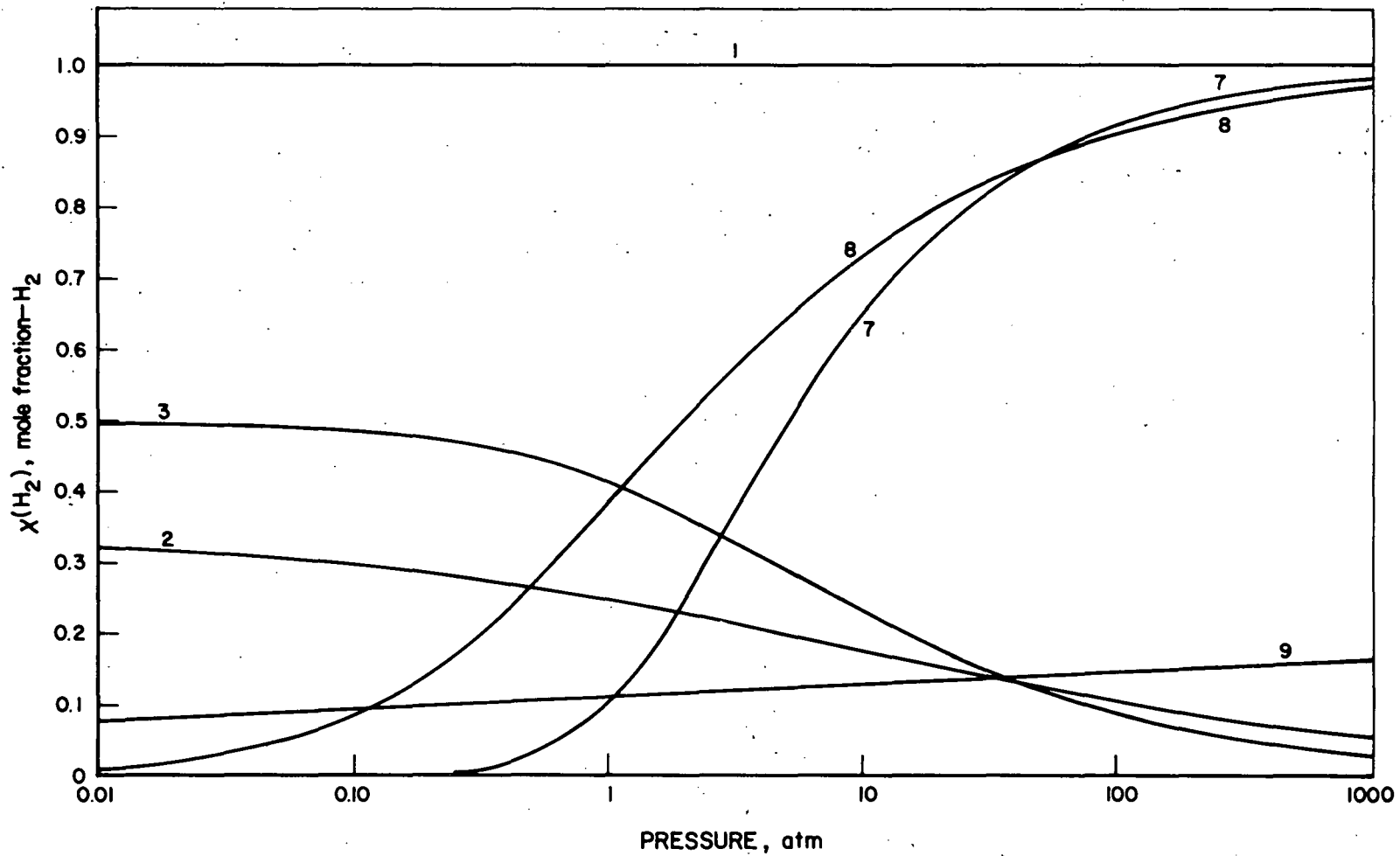### Curve 1. $(1, \infty)$; $\bar{\alpha} = 1$, $R = \infty$

This is a relatively important case numerically, representative of reactions having no gaseous reactants. A typical member of this class is a manganese oxide-sodium hydroxide cycle:
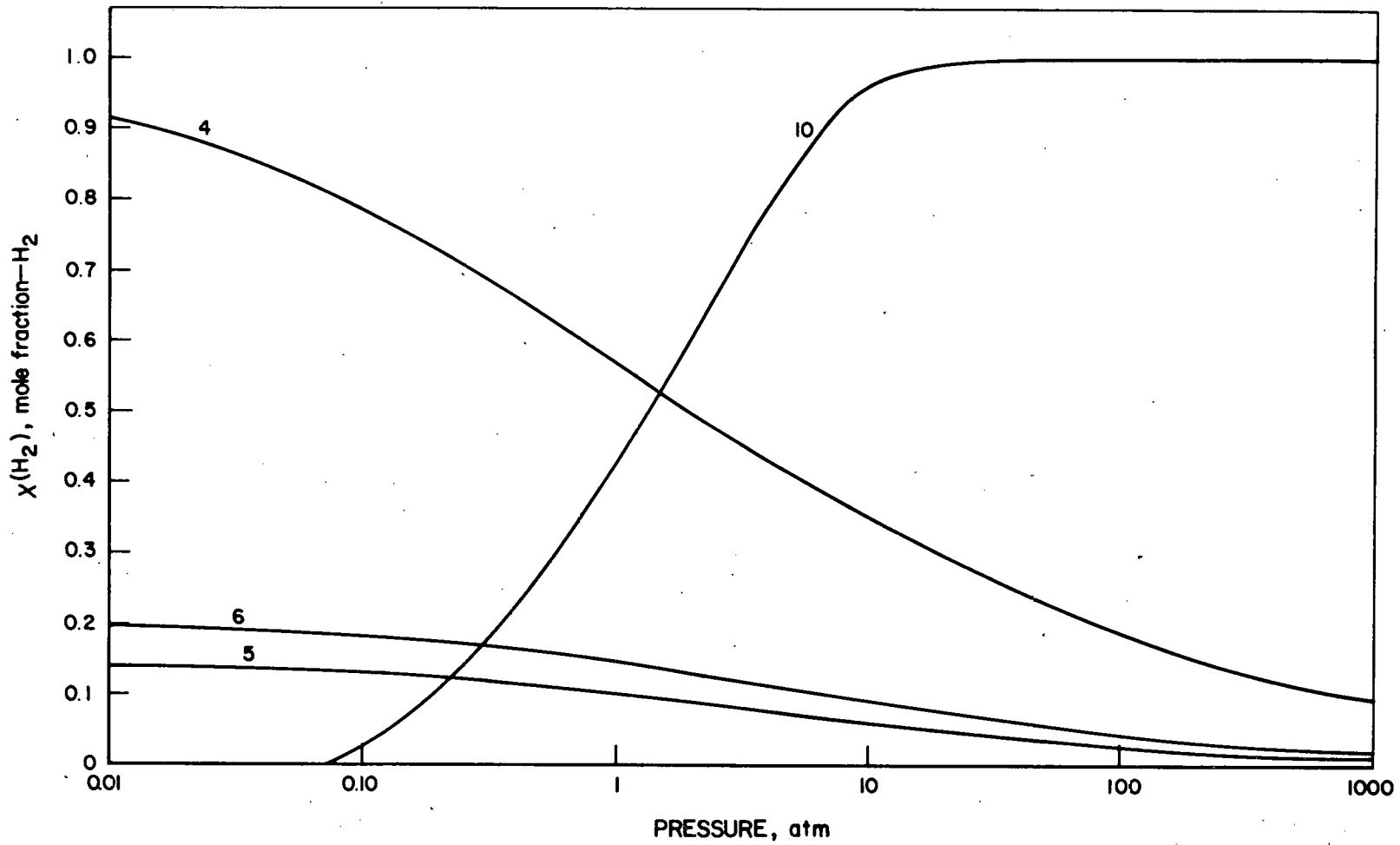
$$3MnO(s) + 2NaOH(s) \rightarrow Mn_3O_4(s) + Na_2O(s) + H_2(g)$$
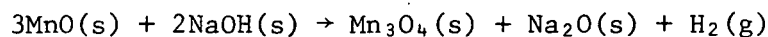
Curve 2. $(1, 3/2)$

As P approaches 0, $\chi(H_2)$ approaches 1/3. The titanium dichloride cycle typifies this class:

$$2TiCl_2(s) + 2HCl(g) \rightarrow 2TiCl_3(g) + H_2(g)$$
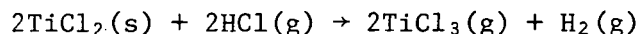
Figure 2.   THE MOLE FRACTION OF HYDROGEN AS A FUNCTION OF EQUILIBRIUM PRESSURE.   ($\Delta G = 0$)

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Figure 2, Cont.   THE MOLE FRACTION OF HYDROGEN AS A FUNCTION OF
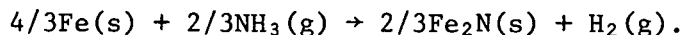EQUILIBRIUM PRESSURE.   ($\Delta G = 0$)

Curve 3.   (1, 2)

As $P \to 0$, $\chi(H_2) \to 1/2$. This hydrogen production step is typical of all steam reforming reactions, such as

$$C(s) + H_2O(g) \to CO(g) + H_2(g).$$

Curve 4.   (1/3, 3/2)

As $P \to 0$, $\chi(H_2) \to 1.0$, for this class of reactions, typified by the iron ammonia cycle

$$4/3Fe(s) + 2/3NH_3(g) \to 2/3Fe_2N(s) + H_2(g).$$

Curve 5.   (3, 7/4)

Even at low pressure, as $P \to 0$, $\chi(H_2) \to 1/7$, this system represents formidable separations difficulties. IGT's cycle B-1 is representative:

$$3FeCl_2(s) + 4H_2O(g) \to Fe_3O_4(s) + 6HCl(g) + H_2(g).$$
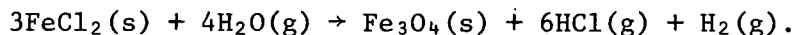
Curve 6.   (2, 5/3)

Like Curve 5, these reactions present formidable problems of separation, as $P \to 0$, $\chi(H_2) \to 0.2$. A moderate-temperature chromium chloride cycle is representative:

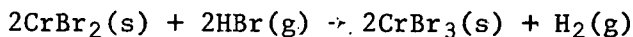$$2CrCl_2(s) + 3H_2O(g) \to Cr_2O_3(s) + 4HCl(g) + H_2(g)$$
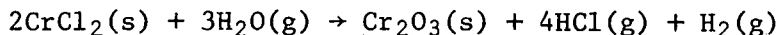
Reactions Favored by Pressure

Curve 7. (−2, 1/3)

Hydrogen production from this reaction is highly favored by increased pressure. $\chi(H_2)$ reaches 0.5 at $P \sim 5.2$ atm.
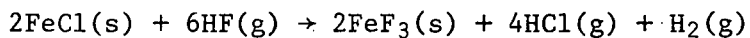
$$Fe_2O_3(s) + 2SO_2(g) + H_2O(g) \to 2FeSO_4(s) + H_2(g)$$
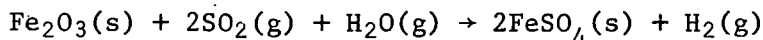
Curve 8.   (−1, 1/2)

Even more favored by increased pressure, $\chi(H_2)$ reaches 0.5 at $P \sim 2$ atm.

$$2CrBr_2(s) + 2HBr(g) \to 2CrBr_3(s) + H_2(g)$$
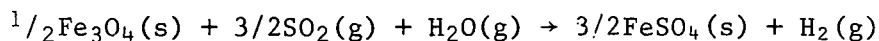
Curve 9.   (−1, 5/6)

A slow, positive monotonic dependence on pressure is shown here, with the hydrogen mole fraction limited by $\chi(H_2) \leq 1/5$

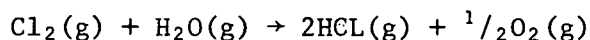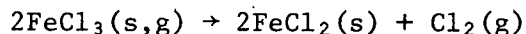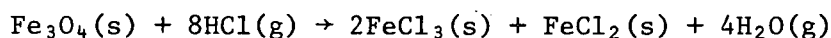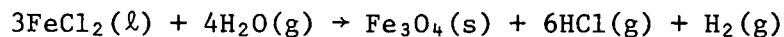$$2FeCl(s) + 6HF(g) \rightarrow 2FeF_3(s) + 4HCl(g) + H_2(g)$$

Curve 10.   (−3/2, 2/5)

A magnetite variant on the equation on curve 7 produced this remarkably fast-rising $\chi(H_2)$. $\chi_{H_2} = 0.5$ for $P \sim 1.4$ atm.

$$^1/_2Fe_3O_4(s) + 3/2SO_2(g) + H_2O(g) \rightarrow 3/2FeSO_4(s) + H_2(g)$$

A CASE STUDY

IGT's cycle B-1 —

$$3FeCl_2(\ell) + 4H_2O(g) \rightarrow Fe_3O_4(s) + 6HCl(g) + H_2(g)$$

$$Fe_3O_4(s) + 8HCl(g) \rightarrow 2FeCl_3(s) + FeCl_2(s) + 4H_2O(g)$$

$$2FeCl_3(s,g) \rightarrow 2FeCl_2(s) + Cl_2(g)$$

$$Cl_2(g) + H_2O(g) \rightarrow 2HCL(g) + ^1/_2O_2(g)$$

has been demonstrated with recycled intermediates [17] and has been analyzed completely.[24]   A load-line efficiency for this cycle has been calculated at IGT and elsewhere, [16] yielding a value of ~18%.   At IGT we used rather conservative assumptions for heat transfer variables and rates, but the prognosis found in this analysis (curve 5) has stood up well.

Cycle B-1 is represented, in general, by curve 5 of Figure 2, and predictions from the equilibrium case for $\Delta G = 0$ are pessimistic.   Deeper analysis of Cycle B-1 indicated that optimistic yields are possible, but the required source temperature must increase.   In Figure 3, the molar ratio of steam to H_2, at equilibrium, $N(H_2O)/N(H_2)$, is plotted as a function of temperature.

Clearly, as $N(H_2O)/N(H_2)$ decreases, the equilibrium temperature becomes unreasonably high, and as the isobars in Figure 3 indicate, high-pressure operation presents us a very formidable problem.

Curve 5 also adumbrates a second difficulty — large separations energies are required because of the small value of $N(H_2)$ and the fact that there are three gaseous species present at equilibrium.   We quantified this tendency, calculating the steam-hydrogen mole ratio vs. temperature for an impure feedstock, $N(HCl)/N(H_2O) = 0.05$.   A series of isobars for this system is shown in Figure 4, and these indicate a substantial shift of values toward higher temperatures.
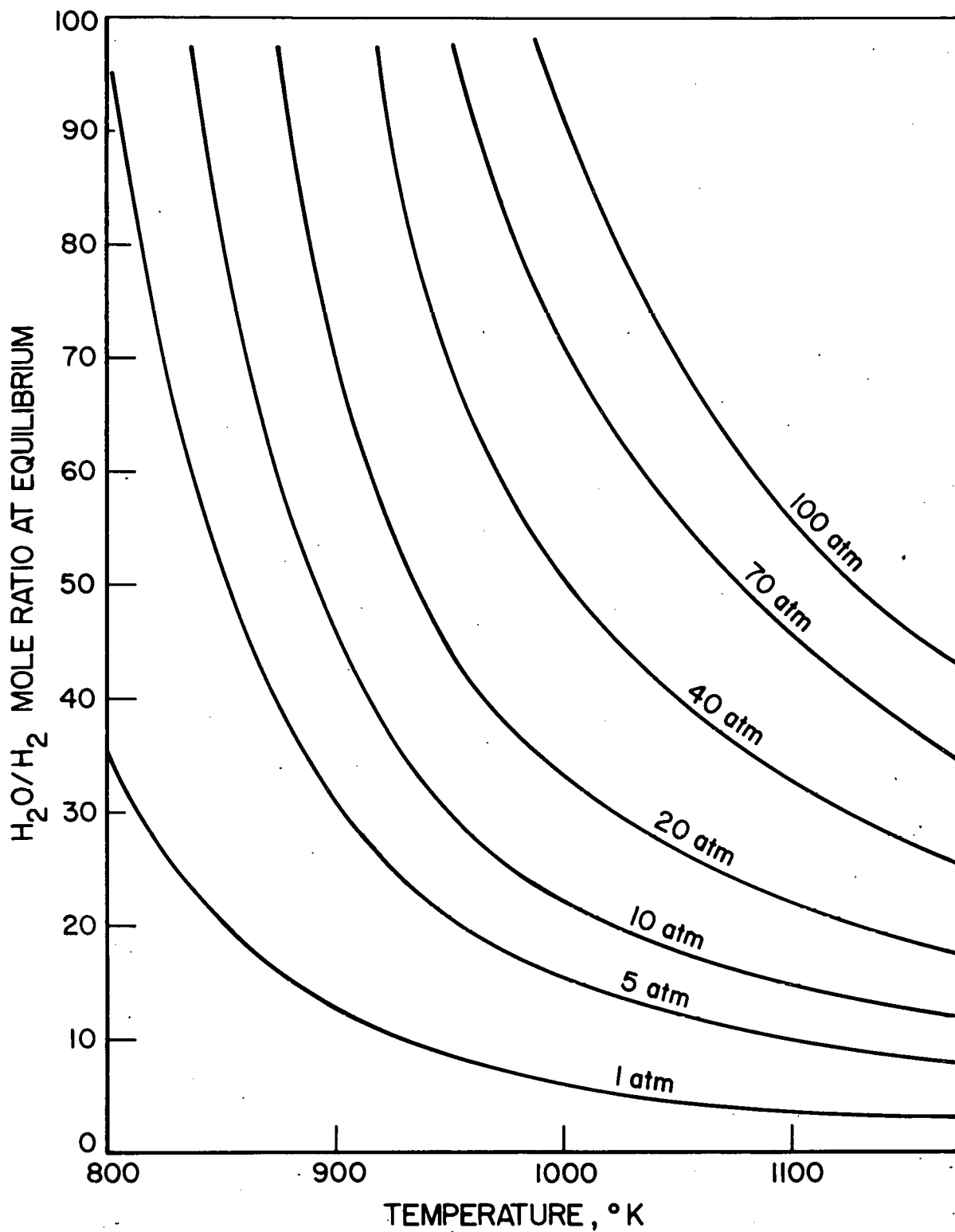
For Cycle B-1, if we choose to minimize separation energy demands by letting $N(H_2O)/N(H_2)$ become small, the required temperature must be quite high. IGT's analysis of this cycle indicated that production of hydrogen at 30
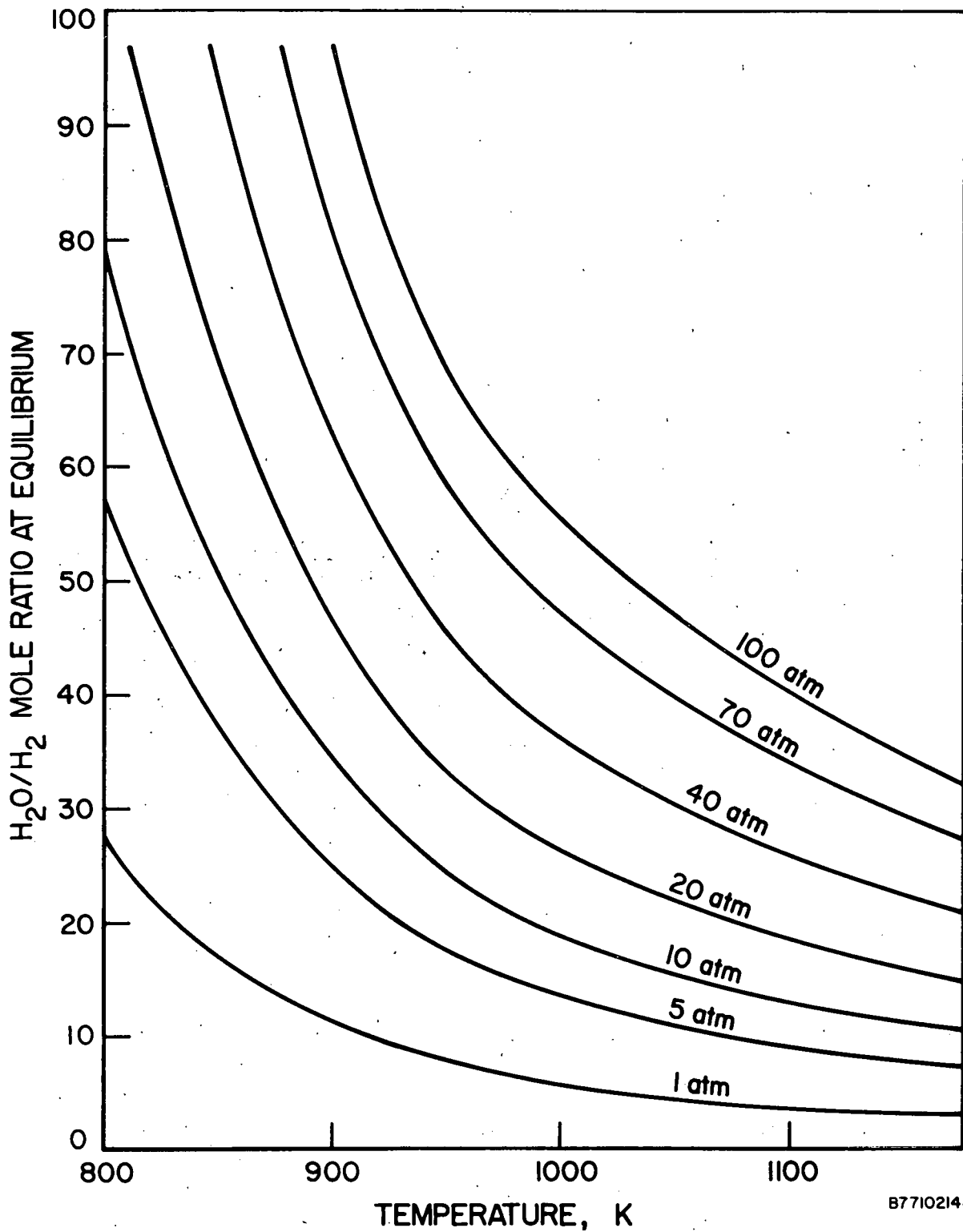
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Figure 3. FERROUS CHLORIDE-STEAM REACTION: EQUILIBRIUM H_2O/H_2 MOLE RATIO AS A FUCTION OF TEMPERATURE (HCl/H_2O FEED RATIO = 0.00)

Figure 4. FERROUS CHLORIDE-STEAM REACTION: EQUILIBRIUM H_2O/H_2 MOLE
RATIO AS A FUNCTION OF TEMPERATURE

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atm, with $N(H_2O)/N(H_2)$ equal to 0.15 required a source temperature of 1300 K, not attainable with nuclear fission process heat supplies.[25]

CONCLUSIONS

Of the 47 hydrogen production steps assessed, 19 are unaffected by system pressure, and 4 have no gaseous reactants. Of the remaining 24 reactions, 14 are favored by pressure, 11 being in the class (—1, 1/2). For this class (see curve 8) the value of increased pressure operation is very high. Only in reaction class (—1, 5/6) is the pressure coefficient of $\chi(H_2)$ marginal. Here the limit on $\chi(H_2)$ as P increases is small because other gaseous products predominate.

Although all analyses based on equilibrium calculations are likely to be pessimistic, the results of this classification of hydrogen production steps show, conclusively, that this kind of examination could be quite useful if made a part of cycle derivation and selection.

Because it is imperative to produce hydrogen at pressure, the value of R is significant, and newly derived cycles with R > 1 will generally require high-temperature operation, but worse, the equilibrium mole fraction of hydrogen, $\chi(H_2)$, is a maximum at zero pressure, meaning the energy of separation increases as pressure increases [$\chi(H_2)$ decreases].

New thermochemical water-splitting cycles will be derived and assessed. The hydrogen production step of any new cycle will fit into one of these classes or will be closely related to it. One can structure, intuitively, the extremes of the equilibrium situation by recognizing that for R > 1, the maximum of $\chi(H_2)$ occurs as P → 0. At all higher pressures $\chi(H_2)$ will be lower.

The critical question at this point is whether it is easy to shift the equilibrium: can product gases be removed rapidly and efficiently enough to permit us to consider such a cycle worthy of further development. This chemical engineering question requires some reflection about possible processes and process equipment to drive the rather poor equilibrium that is under consideration. For cases where R < 1, $\chi(H_2)$ is a maximum for P → ∞, the value of the maximum $\chi(H_2)$ depends on the number of gaseous product species.

This analysis clearly indicates that our cycle derivation procedure should concentrate on cycles in which the hydrogen production step has the following characteristics:

- R < 1

- The only gaseous product is H_2

- A large number of gaseous reactants.

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APPENDIX

Listed below are the cycles examined in this work:

Table A-1. HYDROGEN PRODUCTION REACTION ACCORDING TO $\bar{\alpha}$, R DESIGNATION

$\bar{\alpha}$	R	Temperature (K)	Reaction
Reactions Independent of Pressure			
0	1	1200	$3/4Fe(s) + H_2O(g) \rightarrow 1/4Fe_3O_4(s) + H_2(g)$
		375	$3FeS(s) + 4H_2O(g) \rightarrow Fe_3O_4(s) + 3H_2S(g) + H_2(g)$
		700	$3FeO(s) + H_2O(g) \rightarrow Fe_3O_4(s) + H_2(g)$
		1075	$FeS(s) + 2FeO(s) + 2H_2O(g) \rightarrow Fe_3O_4(s) + H_2S(g) + H_2(g)$
		700	$3/4Mn(s) + H_2O(g) \rightarrow 1/4Mn_3O_4 + H_2(g)$
		875	$3MnS(s) + 4H_2O(g) \rightarrow Mn_3O_4(s) + 3H_2S(g) + H_2(g)$
		700	$2HI(g) \rightarrow I_2(g) + H_2(g)$
		675	$1/2Sn(l) + H_2O(g) \rightarrow 1/2SnO_2(s) + H_2(g)$
		400	$Cd(s) + H_2O(g) \rightarrow CdO(s) + H_2(g)$
		900	$Zn(l) + H_2O(g) \rightarrow ZnO(s) + H_2(g)$
		700	$CO(g) + H_2O(g) \rightarrow CO_2(g) + H_2(g)$
		1200	$2CbO_2(s) + H_2O(g) \rightarrow Cb_2O_5(s) + H_2(g)$
		1000	$1/2Mo(s) + H_2O(g) \rightarrow 1/2MoO_2(s) + H_2(g)$
		400	$2K(l) + H_2O(g) \rightarrow K_2O(s) + H_2(g)$
		800	$SnO(s) + H_2O(g) \rightarrow SnO_2(s) + H_2(g)$
		1000	$1/2W(s) + H_2O(g) \rightarrow 1/2WO_2(s) + H_2(g)$
		400	$WO_2(s) + H_2O(g) \rightarrow WO_3(s) + H_2(g)$
		500	$FeS(s) + H_2S(g) \rightarrow FeS_2(s) + H_2(g)$
		900	$Ce_2O_3(s) + H_2O(g) \rightarrow 2CeO_2(s) + H_2(g)$
Reactions Favored by Pressure			
-2	$1/3$	400	$Fe_2O_3(s) + 2SO_2(g) + H_2O(g) \rightarrow 2FeSO_4(s) + H_2(g)$
$-3/2$	$2/5$	400	$1/2Fe_3O_4(s) + 3/2SO_2(g) + H_2O(g) \rightarrow 3/2FeSO_4(s) + H_2(g)$
-1	$5/6$	400	$2FeCl_2(s) + 6HF(g) \rightarrow 2FeF_3(s) + 4HCl(g) + H_2(g)$
-1	$1/2$	400	$2/3Fe(s) + 2HF(g) \rightarrow 2/3FeF_3(s) + H_2(g)$
		300	$2MnF_2(s) + 2HF(g) \rightarrow 2MnF_3(s) + H_2(g)$
		300	$Cu(s) + 2HF(g) \rightarrow CuF_2(s) + H_2(g)$
		700	$2Cu(s) + 2HCl(g) \rightarrow 2CuCl(s) + H_2(g)$
		525	$Hg(l) + 2HBr(g) \rightarrow HgBr_2(l) + H_2(g)$
		375	$2Cs(l) + 2H_2O(g) \rightarrow 2CsOH(l) + H_2(g)$
		300	$2VCl_2(s) + 2HCl(g) \rightarrow 2VCl_3(s) + H_2(g)$
		425	$Ni(s) + 2HI(g) \rightarrow NiI_2(s) + H_2(g)$
		400	$2CrBr_2(s) + 2HBr(g) \rightarrow 2CrBr_3(s) + H_2(g)$
		400	$2SmCl_2(s) + 2HCl(g) \rightarrow 2SmCl_3(s) + H_2(g)$
		500	$TeCl_2(s) + 2HCl(g) \rightarrow TeCl_4(s) + H_2(g)$
Reactions Not Favored by Pressure			
$1/3$	$3/2$	1000	$4/3Fe(s) + 2/3NH_3(g) \rightarrow 2/3Fe_2N(s) + H_2(g)$
$3/10$	$1/10$	1200	$3/10FeS(s) + H_2O(g) \rightarrow 1/10Fe_3O_4(s) + 3/10SO_2(g) + H_2(g)$
1	∞	300	$3MnO(s) + 2NaOH(s) \rightarrow Mn_3O_4(s) + Na_2O(s) + H_2(g)$
		975	$2KOH(l) + 2K(l) \rightarrow 2K_2O(s) + H_2(g)$
		300	$CuO(s) + H_2SO_3(aq) \rightarrow CuSO_4(aq) + H_2(g)$
1	2	1100	$C(s) + H_2O(g) \rightarrow CO(g) + H_2(g)$
		1000	$C(s) + CdO(s) + H_2O(g) \rightarrow CdO(s) + CO(g) + H_2(g)$
1	$3/2$	1000	$2TiCl_2(s) + 2HCl(g) \rightarrow 2TiCl_3(g) + H_2(g)$
2	$5/3$	400	$2CrCl_2(s) + 3H_2O(g) \rightarrow Cr_2O_3(s) + 4HCl(g) + H_2(g)$
		1200	$2SmCl_2(s) + 3H_2O(g) \rightarrow Sm_2O_3(s) + 4HCl(g) + H_2(g)$
3	∞	775	$Sr_3U_2O_8(s) + 3Sr(OH)_2(s) \rightarrow 2Sr_3UO_6(s) + 2H_2O(g) + H_2(g)$
3	$7/4$	1200	$3FeCl_2(s) + 4H_2O(g) \rightarrow Fe_3O_4(s) + 6HCl(g) + H_2(g)$
		1200	$3MnCl_2(s) + 4H_2O(g) \rightarrow Mn_3O_4(s) + 6HCl(g) + H_2(g)$
		1200	$2CeCl_3(l) + 4H_2O(g) \rightarrow 2CeO_2(s) + 6HCl(g) + H_2(g)$

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