

Hydrogen production through hydrolysis of NaBH_4 : The use of catalysts containing Pt and Pt-Ru.

Antonio Carlos Caetano of Souza

José Luz Silveira

caetanodesouza@yahoo.com.br, caetano@feg.unesp.br

joseluz@feg.unesp.br

Department of Energy, São Paulo State University (UNESP)

Av. Ariberto Pereira da Cunha, 333 - 12516-410, Guaratinguetá, SP, Brazil

Yohannes Kiros

Rolando Zanzi

yohannes@ket.kth.se

rolando@ket.kth.se

Department of Chemical Engineering and Technology (Division of Chemical Reaction

Engineering), Royal Institute of Technology (KTH)

Stockholm, Sweden.

Abstract. Several works about hydrolysis of NaBH_4 utilizing various catalysts (such as catalysts containing Pt or Ru) are available in the literature. Investigations involving NaBH_4 has increased due to the possibility to produce hydrogen using simple and safe systems, even at room temperatures with very high efficiencies. A solution containing a gravimetric composition of 10%wt. NaOH, 10%wt. NaBH_4 and 80%wt. H_2O was utilized and the reaction was initiated immediately as soon as this solution was put in the chosen catalysts, in this case, catalysts containing Pt and mixtures of Pt-Ru. Catalysts containing Pt and Pt-Ru presented high yields of hydrogen after the solution being inserted in the reaction vessel several times. In this study it was found out that the rates of hydrogen production were increased with catalysts containing Pt and Pt-Ru (99 and 96% of theoretical hydrogen production respectively). The catalysts containing Pt presented higher production rate, while the catalysts containing the mixed Pt-Ru presented a quasi-linear production, e.g., stable production rate.

Keywords: hydrolysis, sodium borohydride, platinum, ruthenium, hydrogen production.

Simbology

PEMFC Proton Exchange Membrane Fuel Cell

1. INTRODUCTION

The use of hydrogen for energy purposes, associated with fuel cells, allows a more-reliable and environmentally friendly energy supply, and substitutes toxic materials such as those encountered in batteries (such as nickel, cadmium, cobalt, and more) (Sodium Borohydride, 2007).

Sodium borohydride (NaBH_4) is a reductor material utilized in some chemical, pharmaceutical and pulp and paper industries (Rohm and Haas - Synthesis technologies, 2007). Its hydrolysis allows a high-purity hydrogen production to be used in fuel cells such as PEMFCs (Proton Exchange Membrane Fuel Cells) (Aiello et al., 1999; Department of Environment and Heritage of Australian Government, 2007). A hydrolysis process could be performed at different portions of reactants, thermodynamic conditions, and catalysts (and its different characterization process). (Schlapbach et al., 2001).

Activated-carbon, ruthenium, cobalt, platinum, nickel, rhodium, palladium, and other metals, and its alloys and salts, and fluoride, chloride and boron could be utilized as catalysts. Various supports have been widely studied such as carbon, resins, and metal alloys. The reactions also could be performed without catalysts, specially with acid or alkaline reactants (Levy et al, 1960; Free Patents Online, 2007; Hua et al, 2003)

The hydrolysis of NaBH_4 is a exothermic reaction. This process could be carried out through a catalytic decomposition as follows:



This reaction has a theoretical efficiency of 10,8%. At 23°C, the saturation of NaBH_4 in a aqueous solution occurs in the moment that its mass concentration attains values greater than 35% (56 g NaBH_4 and 100 g water). This hydride contains an amount (in mass) of hydrogen greater if compared to various metallic hydrides and hydrocarbons (Richardson at al., 2005).

The obtained values of heat of formation of previous reaction in several works are different. Table 1 compares this values. And Table 2 shows activation energies from various works:

Table 1. Heat of formation in the hydrogen production by cited systems

Authors:	Utilized catalysts:	Heat of formation (kJ / mol H_2):
Zhang et al. (2007)	RuCl_3	210 ± 11
Zhang et al. (2007)	HCl	227 ± 8
Kojima et al. (2002)	-	217
Suda et al. (2001)	-	225
Wu et al. (2004)	Pt - carbon	217
Zhang et al. (2007)	Ru - carbon	210

The stabilization of solution is generally obtained through the use of alkaline species such as LiOH, KOH and NaOH. The ultimate one is the most utilized due to the low cost (Kojima et al., 2002).

2. EXPERIMENT DESCRIPTION

The experiments were performed in the Department of Chemical Engineering and Technology (Division of Chemical Reaction Engineering) - Royal Institute of Technology - in Stockholm (Sweden).

Firstly, some catalysts were prepared for this experiment, as follows:

- Catalyst containing 10%wt. platinum (Pt) - 120 mg
- Catalyst containing 10%wt. platinum and ruthenium (Pt-Ru) - 110 mg.

Table 2. Activation energy to hydrolysis of NaBH₄

Authors:	Utilized catalysts:	Activation energy (kJ/mol H ₂):
Hua et al. (2003)	Ni _x B	38
Amendola et al. (2000) ¹	Ru - IRA 400	47
Amendola et al. (2000) ²	Ru - IRA 400	56
Kaufman et al. (1985)	Co	75
Kaufman et al. (1985)	Ni	71
Kaufman et al. (1985)	Ni	63
Simagina et al. (2005) ²	1% Rh/Al ₂ O ₃	50,6 ± 1,3
Simagina et al. (2005) ³	1% Pt/Al ₂ O ₃	56,9 ± 0,9
Peña-Alonso et al. (2007)	Pt/Pd-Si	19
Zhang et al. (2007)	Ru-carbon	66,9

Both are carbon-supported catalysts. Carbon-supported platinum catalysts are one of the most-effective materials to be utilized in catalysts and also as cathodes in fuel cells (Ma et al., 2006).

Subsequently a simple system to perform the reaction was mounted, as seen on the Fig. 1:



Figure 1 - System of hydrogen production

An aqueous solution containing 10% wt. NaOH and 10% wt. NaBH₄ was produced to the reaction. Firstly the NaOH was diluted into the water. Subsequently, NaBH₄ was added in the solution. An increase of temperature during preparation of solution was verified during application of NaOH and during application of NaBH₄, being possible to observe a non-controlled hydrogen production.

Works developed by Amendola et al. (2000²) and Suda et al. (2001) cited the influence of temperature in the rate of hydrogen production, having a major rate of production as soon as the hydrolysis process was developed at higher temperature. This phenomenon also occurs in other hydrogen production processes such as steam reforming (Souza, 2005).

Cited in the work of Hua et al. (2003), the hydrolysis of NaBH₄, if submitted at temperatures greater than 25°C, the efficiency of reaction might attain about 90%, diminishing at about 78%, at 15°C. As seen in the work of Richardson et al. (2005), the increase of 5°C in the temperature of reaction might increase the rate of hydrogen production at 50%.

Figure 2 depicts the variation of temperature during preparation of solution and during the reaction catalytic. During preparation of solution, the highest temperatures were verified immediately after mixing NaOH with water and five minutes after mixing NaBH₄ in this mixture. This same figure depicts variation of temperature during catalytic reaction.

¹ Solution containing 5% Ru, 7.5% NaBH₄, 1% NaOH, and 91.5% H₂O.

² At 30, 40 and 50°C.

³ At 30, 40 and 50°C.

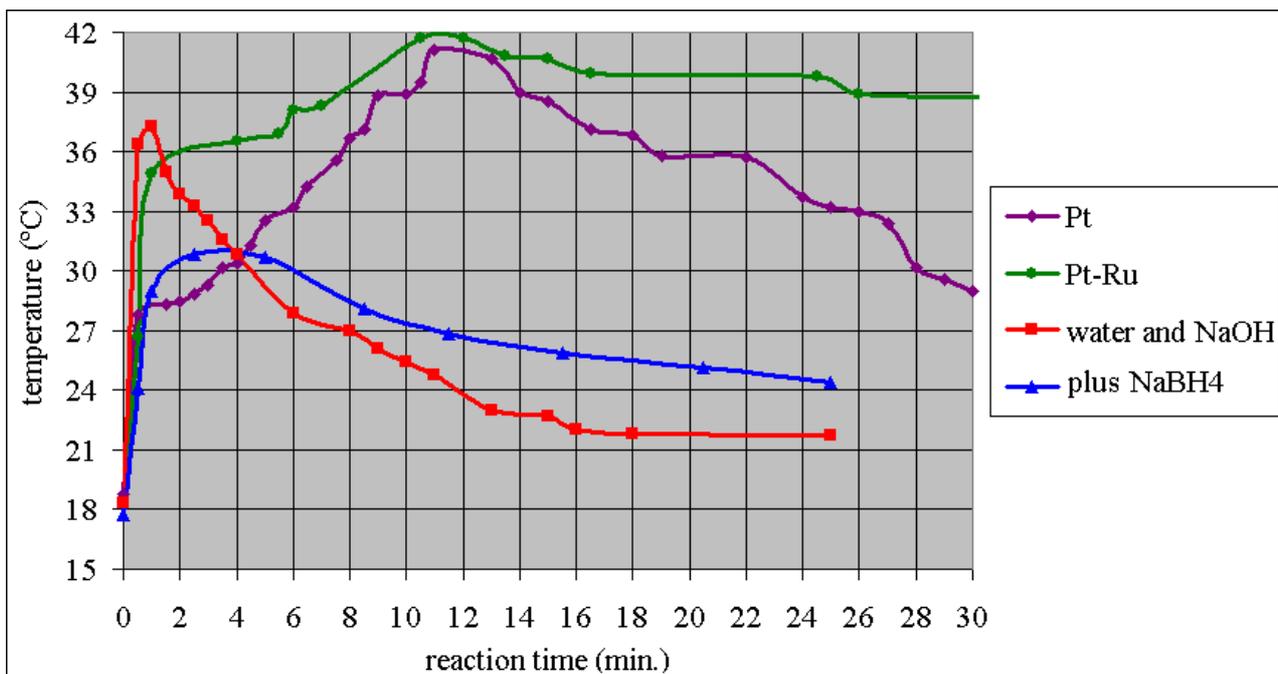


Figure 2 - Evolution of temperatures during preparation of solution and during catalytic reactions

Among catalytic reactions, a small decrease of temperature of reaction utilizing catalysts Pt-Ru occurred after attaining its major value after 9 minutes of reaction was initiated), in contrary to the catalyst containing Pt, where major temperatures decreases were verified. Higher temperatures at first minutes of a catalytic reaction were cited in various works (Kaufman et al., 2005; Simagina et al., 2005).

Immediately after preparation of solution, one of the catalysts was applied in a flask where a chemical reaction was carried out. Subsequently, a volume of 2 ml of this solution was applied into the catalyst. Immediately the catalytic generation of hydrogen was occurred. At first 40 minutes, the volume of generated hydrogen was measured at each minute. After this period, these measurements were performed at each 5 minutes, finalizing as soon as the reaction finished. After hydrogen production, an additional volume of 2 ml was applied and the hydrogen was measured. Five applications of 2 ml of solution were carried out to evaluate performance of each catalyst.

As depicted in the Fig. 3 (which shows the solubility of NaBO_2), cited by Garrett (1998), the solubility of NaBO_2 is about 18%wt. at 18°C (temperature which the catalytic reaction could commencing). After 30 minutes of catalytic reaction, the temperature of solution was about 22°C (resulting in a amount of NaBO_2 of about 22%wt.). In this case, an additional water of reaction is utilized to produce sodium metaborate tetrahydrate ($\text{NaBO}_2 + 4 \cdot \text{H}_2\text{O}$).

3. RESULTS OF HYDROGEN PRODUCTION

From the first up to fifth application of solution, they were verified the highest rate and volume of hydrogen production in the use of catalyst containing Pt. The efficiencies and the time of reaction for each catalyst (after first and fifth applications of solution) are contained in the Table 3. The evolution of hydrogen production is depicted in the Fig. 4.

Subsequently, this solution was applied various times immediately after finalizing a hydrolysis process. In catalysts containing Pt-Ru, every times, a quasi-linear hydrogen production was detected. The same phenomenon was seen in a catalyst containing Pt, however only after fifth application of solution, as seen on the Fig. 4.

In subsequent applications of solution, it was verified that the hydrogen production finalized after greater periods, having smaller and more stable production rates. The smaller rates of hydrogen production occurred because the contact surface area of these catalysts decreased due to filling of pores by solid products of reaction.

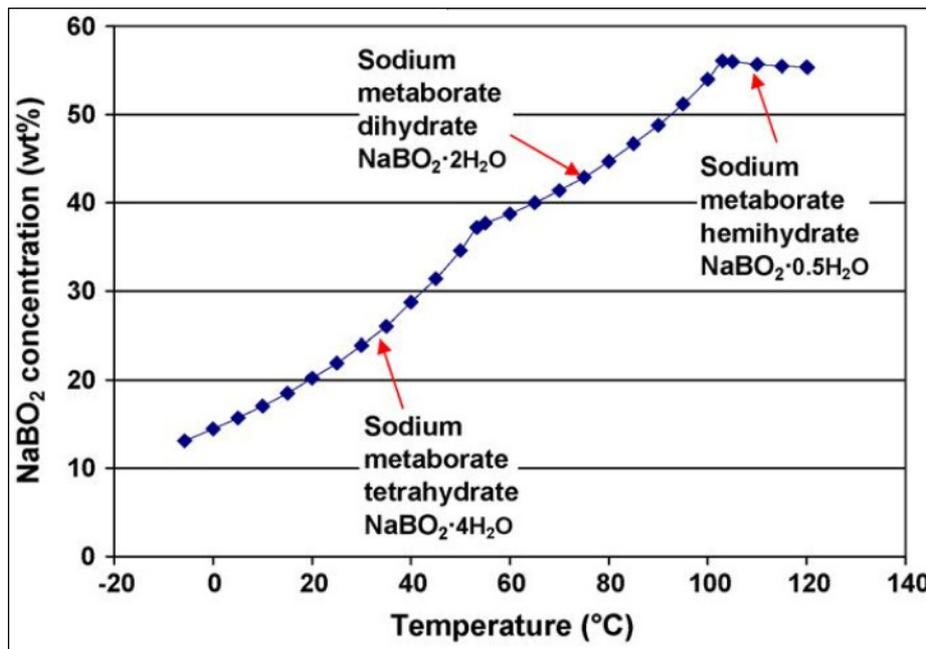


Figure 3 - Diagram of NaBO₂ solubility (Garrett, 1998)

Table 3. Efficiency and time of hydrogen production

First application		
	PtRu	Pt
efficiency of generation (%)	87,5	92,0
Minutes	230	130
From first to fifth application		
	PtRu	Pt
efficiency of generation (%)	98,5	98,3
Minutes	550	170

The occurred phenomenon by two catalysts is similar at phenomenon verified in the work described by Kim et al. (2004), which utilized a catalyst containing nickel. In this work and in the work described by Kim et al. (2004), from second to fifth application of solution small variations in the hydrogen production were encountered. Only in this work (among all references cited) the description of hydrogen production applying various times the studied solution was encountered.

The designed work by Zhang et al. (2007) also depicts the degradation of utilized catalysts in function of time. However, in this work, the solution is utilized at continuous flow.

The hydrolysis reaction for hydrogen generation was performed at environment temperature (18 to 20°C).

The rates of hydrogen production were compared to the obtained rates in other works such as described by Krishnan et al. (2005), which detected a major rate and also a major volume of hydrogen production as soon as solutions containing 10%wt. NaBH₄, were utilized, in both catalysts, comparing to solutions containing 5, 15 or 20%wt. of NaBH₄. However the hydrogen productions in the last two fractions were more stable to the other fractions.

In the work depicted by Pinto et al. (2006), it was cited that the rate of hydrogen production was higher in a solution containing 10%wt. of NaBH₄ if compared to of hydrogen production at 20wt. of NaBH₄. This fact occurs due to a greater production of NaBO₂, which could surpass its solubility, precipitating in the solution and accumulating in the catalyst pores.

As seen on the majority of the verified works, volumes of production during the time of production were included. However, in this work, analyses of volumes of hydrogen production with the masses of utilized catalysts were also included. Both results (from this and from an other work) were cited in the Fig. 5.

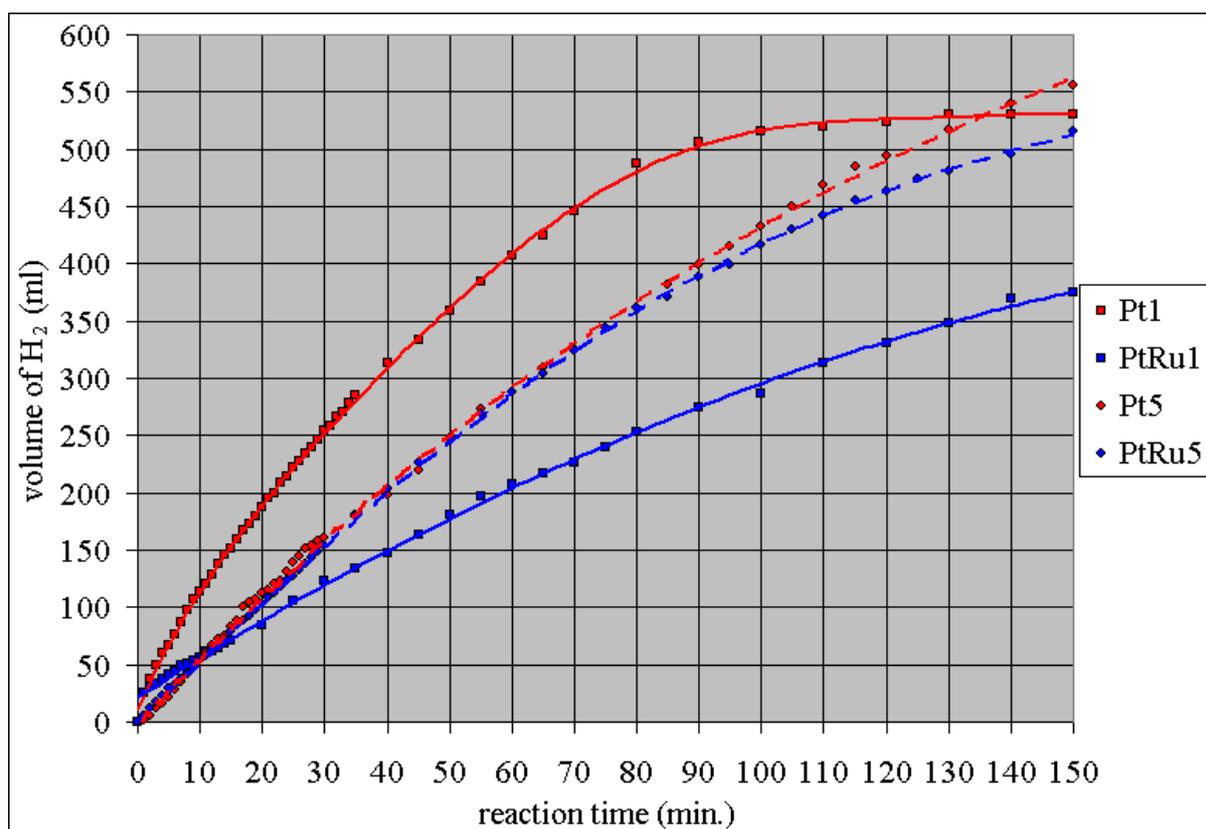


Figure 4 - Volumes of hydrogen production in the first and fifth time when the solution was applied

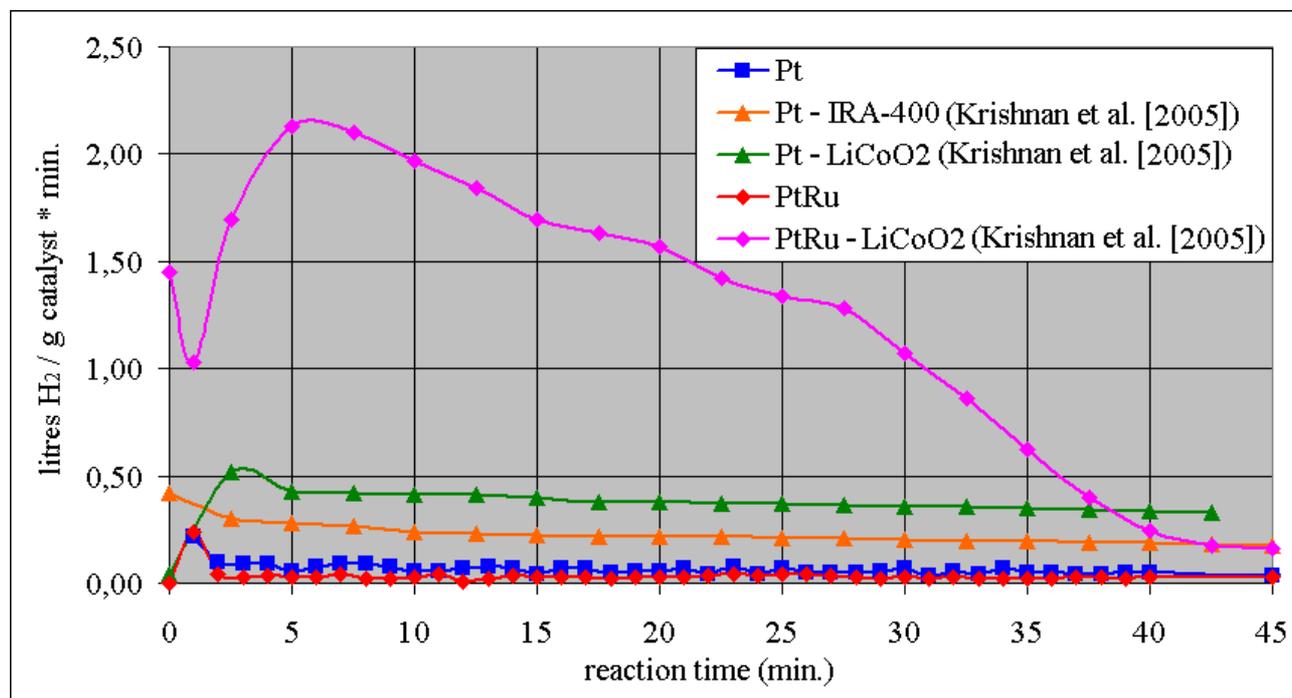


Figure 5 - Specific volumes of hydrogen production utilizing catalysts containing Pt e Pt-Ru in function of time

The efficiency of hydrogen generation could also be evaluated and compared to the efficiencies of generation described in other works, as depicted in the Figs. 5 to 7, which compares catalysts containing Ru e Pt-Ru evaluated in this and in other works.

In this work volumes of produced hydrogen by the time, amount of catalyst and amount of NaBH_4 were obtained. Only in the work performed by Peña-Alonso et al. (2007) is possible to

observe similar measurements. In this case, volumes of produced hydrogen by the time, catalyst mass and molar concentration of NaBH_4 were obtained.

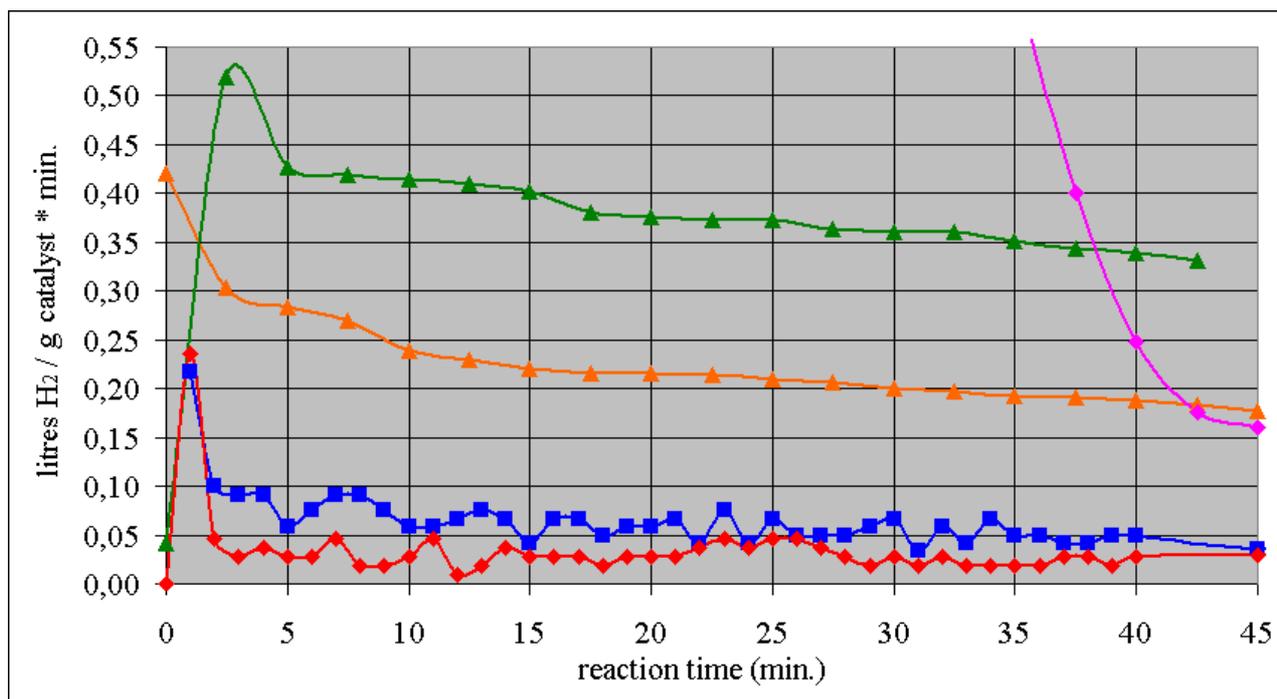


Figure 6 - Specific volume of hydrogen production utilizing catalysts containing Pt e Pt-Ru in function of time (a more-detailed version of previous figure)

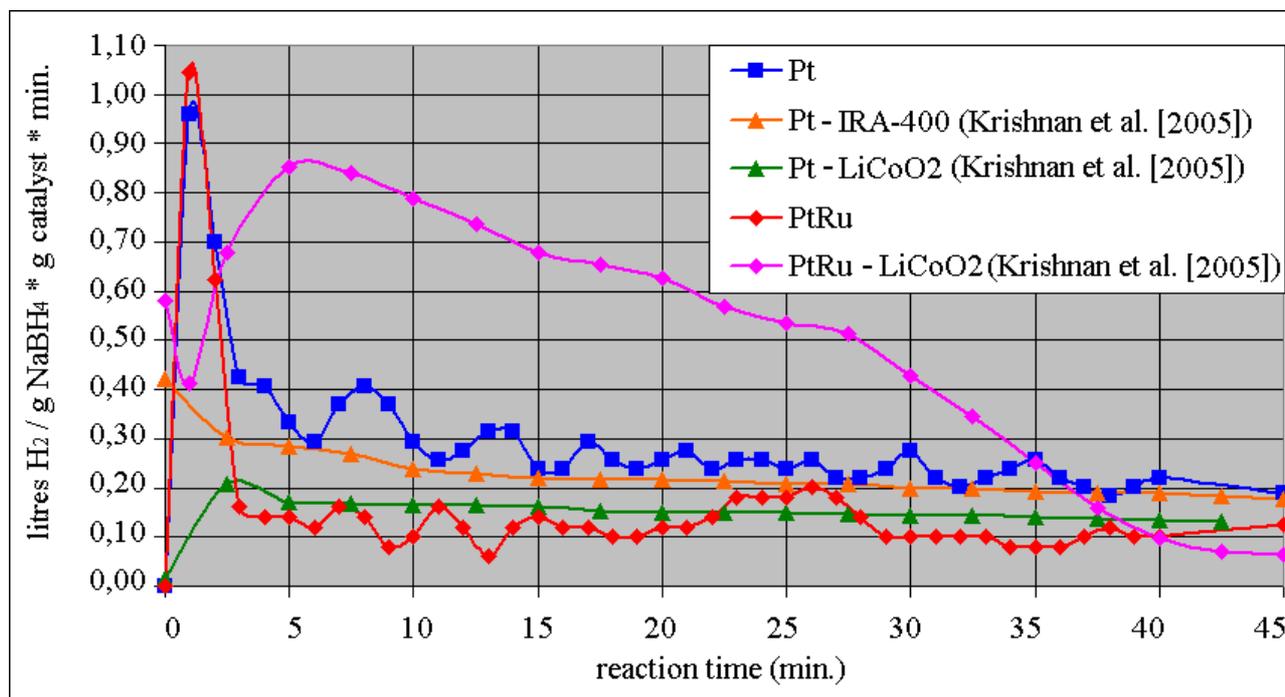


Figure 7 - Hydrogen production utilizing catalysts containing Pt and Pt-Ru,

The comparison among specific volumes of produced hydrogen in this and the cited experiments in this work are depicted in the Figs. 5 a 7. In the Fig. 5, the evolution of hydrogen production by the time and amount of catalyst is depicted, which could be utilized to determine the best conditions of catalysis, with objective to determine the highest rates of hydrogen production. More accurate results are depicted in the Fig. 5, where experiments containing the lowest rates are depicted. In that figure, approximated values were encountered.

However in the cited results in these figures the influence of reactant NaBH_4 in the catalysis is not included. This fact would permit assessing the performance of experiments more accurately. The greatest differences among different registered experiments in the Figs. 5 e 7 were diminished as soon as mass of NaBH_4 was inserted in the calculations.

Certainly a minor volume of hydrogen could be produced with a minor mass of catalysts or minor concentration of active materials such as Pt e Pt-Ru, verified in this work. However, depending on the reaction conditions, major specific volumes of hydrogen might be detected, occasioning in minor generation costs, Major specific volumes of hydrogen also could be generated inserting solutions with minor amounts of NaBH_4 , which could result in minor production costs.

In the near future experiments utilizing smaller catalysts and minor amount of NaBH_4 could be performed to obtain major specific volumes of hydrogen and, specially, minor costs in its production.

About the utilized catalysts in this experiment, the greatest rates of production of hydrogen were encountered and cited in the Figs. 5 e 6 due to the influence of reactant NaBH_4 in the results of reaction catalytic.

Increases and decreases of hydrogen rate were depicted in this experiment. This fact is due to the spread of part of this catalyst material in this solution. This fact also occurred after subsequent applications of solution in these catalysts.

The capacity of permeability of the solution at each catalyst is also responsible by variation of hydrogen production rate. In this case, the capacity of permeability of solution probably attained a maximum in the first minutes of reaction.

The results depicted in red and blue spots were obtained in this experiment. The findings about the studied catalysts, the compositions of utilized solutions, the highest rates of obtained hydrogen production and their generation efficiencies (ratio between theoretical generation of hydrogen and accounted generation during generation) are cited in the table 4.

Table 4. Efficiency and time of hydrogen production

Catalyst:	Support:	Fraction of NaOH (%wt.):	Fraction of NaBH_4 (%):	Higher rates of production ($\text{I}_{\text{H}_2} / \text{g}_{\text{cat}} * \text{g}_{\text{NaBH}_4} * \text{min.}$):
Pt (10%)	carbon	10	10	0,95
Pt-Ru (10%)	carbon	10	10	1,05
Ru (5%)	IRA 400	1	1	0,58 (a 25°C)
Pt-Ru (10%)	LiCoO_2	5	10	0,864 (a 25°C)
Pt (10%)	LiCoO_2	5	10	0,41 (a 25°C)
Pt (5,5%)	IRA 400	5	10	0,167 (a 25°C)

Catalyst:	Efficiency of hydrogen generation (%):	Time of production (min.):	References:
Pt (10%)	92	130	in this work
Pt-Ru (10%)	87,5	230	In this work
Ru (5%)	92	37,5	Amendola et al. (2000 ¹)
Pt-Ru (10%)	89	45	Krishnan et al. (2005)
Pt (10%)	57	42,5	Krishnan et al. (2005)
Pt (5,5%)	64	45	Krishnan et al. (2005)

Generally the times of reaction are lower in reactions carried out by solutions containing minor rates of NaBH_4 and NaOH as cited previously. This phenomenon could be sought in the previous figure. In the reaction described by Amendola et al. (2000¹), due to the minor rate of NaOH and NaBH_4 , the reaction was carried out in a period of time lower than 40 minutes, having a generation efficiency of 92%. Major periods of time were necessary to the depicted reactions in this work and in the work performed by Krishnan et al. (2005). Both works contained higher mass fractions of reactants NaOH and NaBH_4 if compared to other works.

After 45 minutes of reaction, in the experiment depicted in this work utilizing catalyst containing PtRu, the accounted theoretical efficiency was about 28%. In the experiment depicted by Amendola et al. (2000¹), about 92% of theoretical efficiency of hydrogen generation was accounted.

While this work shows a major hydrogen production utilizing a catalyst containing a carbon-supported catalyst containing only Pt to the catalyst utilizing the same support and containing Pt-Ru, in the work performed by Krishnan et al. (2005), utilizing a support of LiCoO₂, the produced volume of hydrogen was greater in a catalyst containing PtRu than the catalyst containing only Ru, whose production was greater if compared to the accounted hydrogen production utilizing a catalyst containing only Pt. However, utilizing IRA-400-supported catalysts, the production by catalysts containing only Pt was greater than the production by catalysts containing only Ru. This fact allows showing the influence of supports in hydrogen generation.

The efficiency of hydrogen generation utilizing catalysts containing only Pt in the experiment cited in this work was 66% if accounted only hydrogen generation after 45 minutes of reaction. In the same period of time, in a work performed by Krishnan et al. (2005), the efficiency of generation in catalysts containing only Pt and IRA-400 as support was 64%, and utilizing catalysts containing only Pt and LiCoO₂ as support, the efficiency of hydrogen generation was 57%.

In this work, the catalysts containing Pt and PtRu presented satisfactory results having inclusively the highest rates of production in the first minutes of generation, if compared to obtained results from other works. The different results were encountered due mainly to the rates of Pt and Pt-Ru in the utilized catalysts and different rates of utilized solution.

In works performed by Xia et al. (2005), Krishnan et al. (2005) and Bai et al. (2006), it was cited that the major rates of hydrogen production were detected in the first five minutes of reaction, having subsequently a slow decrease of production rate.

Some experiments described in other works were performed at small periods, becoming restricted possible comparisons with experiments described in this work. Various works do not depict some conditions too important in this kind of study such as temperature and rates of reactants of a solution, becoming more difficult comparisons among results from various works.

4. CONCLUSIONS

The hydrolysis of NaBH₄ for hydrogen generation is an effective way to produce high-purity hydrogen. This process does not need an external source of heat to perform reactions, diminishing costs to the process.

Differences among volumes of generated hydrogen and among rates of generation were observed in the studied catalysts in this and other works (whose references are encountered in this work).

Among utilized catalysts in this experiment, major rates of hydrogen production utilizing catalyst containing Pt were observed. The production rates increased due to subsequent applications of solution, in both catalysts.

Figure 2 shows the behaviour of temperatures of studied reactions utilizing two catalysts. Despite the presence of major temperatures with the catalyst containing Pt-Ru, the difference among the greatest temperatures registered (at about nine minutes after initiating the reactions) is low. As cited previously the registered temperatures by catalyst containing Pt-Ru present a low decrease after attaining its higher value. This phenomenon could explain the major stability in the hydrogen production comparing to the production by catalyst that contains only Pt, where temperature of reaction decreased sharply.

If compared to results obtained in other works, it is possible to observe that utilizing solutions containing minor amounts of NaOH and NaBH₄, the rates of hydrogen production were greater as described previously. However, this fact was not responsible by overall volume total of produced hydrogen.

In works performed by Kojima et al. (2002) and Simagina et al. (2005), the theoretical efficiencies of hydrogen generation without catalysts were observed. In these cases the values were extremely low, showing the need of catalysts in this type of reaction.

To a future study, a development of other techniques of assembly of catalysts could be suggested to obtain more-resistant ones, and diminishes dispersion of some catalytic material. According to a work performed by Xia et al. (2005), which utilized catalysts containing only Ru, a

major amount of NaBH₄ in a solution could contribute to an overall spread of a catalyst, which in that case occurred as soon as the solution contained 20%wt. of NaBH₄.

The possibility of the use of catalysts containing higher amounts of Pt or Pt-Ru could be studied subsequently, with the objective to design a more-efficient hydrolysis of NaBH₄ with major rates and efficiency of hydrogen production as described in a work performed by Bai et al. (2006). A research about the influence of these catalysts at an application of a solution flow (and their possible variations), usually applied to study the behaviour of hydrogen production, could be also suggested.

REFERENCES

- Aiello R; Sharp J. H.; Matthews M. A., 1999. Production of hydrogen from chemical hydride via hydrolysis with steam. *International Journal of Hydrogen Energy*, vol. 24, pp. 1123-1130. Elsevier.
- Amendola, S. C.; Sharp-Goldman, S. L.; Janjua, M. S.; Kelly, M. T.; Petillo, P. J.; Binder, M, 2000¹. A safe, portable, hydrogen gas generator using aqueous borohydride solution and Ru catalyst, *International Journal of Hydrogen Energy*, vol. 25, pp. 969-975. Elsevier.
- Amendola, S. C.; Sharp-Goldman, S. L.; Janjua, M. S.; Kelly, M. T.; Petillo, P. J.; Binder, M., 2000². An ultrasafe hydrogen generator: aqueous, alkaline borohydride solutions and Ru catalyst, *Journal of Power Sources*, vol. 85, pp. 186-189. Elsevier.
- Bai, Y; Wu, C; Wu, F; Yi, B., 2006. Carbon-supported platinum catalysts for on-site hydrogen generation from NaBH₄ solution. *Materials Letters*, vol. 60, pp. 2236-2239. Elsevier.
- Department of Environment and Heritage of Australian Government. *Boron & Compounds Fact Sheet*. Available at: <http://www.npi.gov.au/database/substance-info/profiles/15.html>. Viewed on July 28, 2007.
- Free Patents Online. *Chemical hydride hydrogen generation system and fuel cell stack incorporating a common heat transfer circuit*. Available at: <http://www.freepatentsonline.com/7045230.html>. Viewed on July 28, 2007.
- Garrett, D. E., 1998. Borates: *Handbook of Deposits, Processing, Properties, and Use*. Academic Press, San Diego - USA.
- Hua D; Hanxi Y; Xinping A; Chuansin C., 2003. Hydrogen production from catalytic hydrolysis of sodium borohydride solution using nickel boride catalyst. *International Journal of Hydrogen Energy*, vol. 28, pp. 1095-1100. Elsevier.
- Kaufman, C. M.; Sen, B., 1985, Hydrogen generation by hydrolysis of sodium tetrahydroborate: effects of acids and transition metals and their salts, *Journal of Chemical Society, Dalton transactions*, vol. 307, pp. 307-313. Elsevier.
- Kim, J. H.; Kim, K. T.; Kang, Y. M.; Kim, H. S.; Song, M. S.; Lee, Y. J.; Lee, P. S.; Lee, J. Y., 2004. Study on degradation of filamentary Ni catalyst on hydrolysis of sodium borohydride. *Journal of Alloys and Compounds*, vol. 379, pp. 222-227. Elsevier.
- Kojima, Y.; Suzuki, K.; Fukumoto, K.; Sasaki, M.; Yamamoto, T.; Kawai, Y.; Hayashi, H., 2002. Hydrogen generation using sodium borohydride solution and metal catalyst coated on metal oxide. *International Journal of Hydrogen Energy*, vol. 27, pp.1029-1034. Elsevier.
- Krishnan, R.; Yang, T. H.; Lee, W. Y.; Kim, C. S., 2005. PtRu-LiCoO₂ - an efficient catalyst for hydrogen generation from sodium borohydride solutions. *Journal of Power Sources*, vol.143, pp. 17-23. Elsevier.

- Levy, A.; Brown, J. B.; Lyons, C. J., 1960, Catalyzed hydrolysis of sodium borohydride, *Industrial & Engineering Chemistry*, vol. 52, pp. 211-214. Elsevier.
- Ma, H; Xue, X; Liao, J; Liu, C; Xing, W., 2006. Effect of borohydride as reducing agent on the structures and electrochemical properties of Pt/C catalyst. *Applied Surface Science*, vol. 252, pp. 8593-8597. Elsevier.
- Peña-Alonso R.; Sicurelli, A.; Callone E.; Carturan, G.; Raj, R., 2007. A picoscale catalyst for hydrogen generation from NaBH₄ for fuel cells. *Journal of Power Sources*, vol. 165, pp. 315-323. Elsevier.
- Pinto, A. M. F. R; Falcão, D. S; Silva, R. A; Rangel, C. M., 2006. Hydrogen generation and storage from hydrolysis of sodium borohydride in batch reactors. *International Journal of Hydrogen Energy*, vol. 31, pp. 1341-1347. Elsevier.
- Richardson, B. S.; Birdwell, J. F.; Pin, F. G.; Jansen, J. F.; Lind, R. F., 2005. Sodium borohydride based hybrid power system. *Journal of Power Sources*, vol. 145, pp.21-29. Elsevier.
- Rohm and Haas - Synthesis technologies. Sodium *Borohydride* (NaBH₄). Available at: <http://www.sodiumborohydride.com/sodiumborohydride.html>. Viewed on July 28, 2007.
- Schlapbach, L.; Züttel, A., 2001. Hydrogen-storage materials for mobile applications. *Nature*, vol. 414, pp. 353.
- Simagina, V. I.; Netskina, O. V.; Komova, O. V.; Stoyanova, I. V.; Gentsler, A. G.; Veniaminov, S. A. Catalysts for hydrogen generation by hydrolysis of sodium borohydride. *Proceedings of International Hydrogen Energy Congress and Exhibition IHEC 2005*. Istanbul, Turkey, 13-15 July 2005.
- Sodium Borohydride. Available at: <http://sodium.borohydride.en.infoax.org>, Viewed on July 28, 2007.
- Souza. A. C. C., 2005. *Technical and economic analysis of a steam reformer of ethanol to hydrogen production*. M.Ing. Thesis, College of Engineering, Campus of Guaratinguetá, São Paulo State University – Brazil (in portuguese).
- Suda, S.; Sun, Y. M.; Liu, B. H.; Zhou, Y.; Morimitsu, S.; Arai, K.; Zhou, Y.; Tsukamaoto, N.; Uchida, M.; Candra, Y.; Li, Z. P., 2001. Catalytic generation of hydrogen by applying fluorinated-metal hydrides as catalysts. *Applied Physics A - Materials Science & Processing*, vol. 72, pp. 209-212. Elsevier.
- Wu, C.; Zhang, H.; Yi, B., 2004. Hydrogen generation from catalytic hydrolysis of sodium borohydride for proton exchange membrane fuel cells. *Catalysis Today*, vol. 93-95, pp. 477-483. Elsevier.
- Xia, Z.T.; Chan, S.H., 2005. Feasibility study of hydrogen generation from sodium borohydride solution for micro fuel cell applications. *Journal of Power Sources*, vol. 152, pp. 46-49. Elsevier.
- Zhang, J.S; Delgass, W.N.; Fisher, T.S., 2007. Kinetics of Ru-catalyzed sodium borohydride hydrolysis. *Journal of Power Sources*, vol. 164, pp. 772-781. Elsevier.
- Zhang, J.; Zheng, Y.; Gore, J. P.; Fisher, T. S., 2007. 1 kWe sodium borohydride hydrogen generation system Part I: Experimental study. *Journal of Power Sources*, vol. 165, pp. 844-853. Elsevier.