

# BIOMASS COMBUSTION SYSTEM IN COGENERATION

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**Rezumat.** Se cunosc din literatura de specialitate tendințele actuale de utilizare a biomasei ca și combustibil neutru din punct de vedere al emisiei de CO<sub>2</sub>. De asemenea, principiul cogenerării este indicat ca fiind superior din punct de vedere economic și implicit pentru reducerea emisiilor poluante față de sistemele clasice de generare a unei singure forme de energie. Prezenta lucrare face referire la arderea biomasei într-un sistem cu cogenerare. Inițial, s-au studiat factorii și parametrii care influențează procesul de ardere al biomasei pe o instalație de ardere în cogenerare CHP (combined heat and power) construită în parteneriat de către compania Magnet-Motor (producătorul german de motoare Stirling), și KÖB (producătorul austriac al instalației de ardere). Instalația de ardere este echipată cu un motor Stirling de 40 kW și este proiectată pentru sistemele individuale de încălzire, funcționând în cogenerare, pe biomasă.

Lucrarea descrie modul de testare a sistemului de ardere și concluziile obținute. Testele preliminare au dovedit că sistemul de ardere ales prezintă câteva neajunsuri, astfel că s-au realizat modificări ale instalației. Rezultatele au fost implementate, realizându-se astfel un sistem de ardere îmbunătățit, cu eficiență superioară, care reprezintă baza unei noi instalații de ardere în cogenerare.

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## INTRODUCTION

Small scale CHP systems offer a considerable additional value for operators of small wood processing companies. They produce residues exceeding their requirements for heat production. Furthermore these residues are normally dry which eases the production of high temperature flue gases and gives more flexibility for partial load operation.

However, all existing systems still suffer from fouling and slagging. The particles in the flue gas deposit on the heat exchangers, forming layers which must be removed manually from time to time; Stirling systems would operate with reduced efficiency in part load operation, as combustion temperatures and flue gas flows decrease in available systems.

The existing CHP system will be improved based on these investigations.

## DESCRIPTION OF THE STIRLING/BIOMASS CHP DEMONSTRATION PLANT

The basic layout of the combustion system is shown in figure 1. The fuel is fed into the primary zone by a stoker feeding system. It burns with primary air sucked into the combustion system by the pressure drop between the combustion chamber and the ambient air. The pressure in the combustion chamber is maintained by the flue gas fan. Partial combustion takes place in the primary zone. The gases leaving this zone are intensively mixed with secondary air by a special fan causing a swirling gas flow in the cylindrical secondary combustion zone. This improves the combustion and

removes particulate solid particles of matter already in the combustion zone. Due to improved gas mixture the air excess ratio can be reduced considerably allowing higher combustion temperatures. This gives following advantages for the integration of a Stirling engine:

- the reduced particulate matter content reduces deposition rates on the heat exchanger surface;
- the higher temperatures are favorable for a higher efficiency of Stirling operation.

Due to these advantages this system was chosen to build up a CHP system. This was done in co-operation of the company Magnet-Motor, manufacturer of Stirling engines and the company KÖB, manufacturer of the Pyrot combustion system. Figure 2 shows the layout of this integrated plant.

The displayed design was chosen to avoid flaps exposed to high temperatures and to enable bypassing of the Stirling engine when the flue gas temperature is too high or too low.

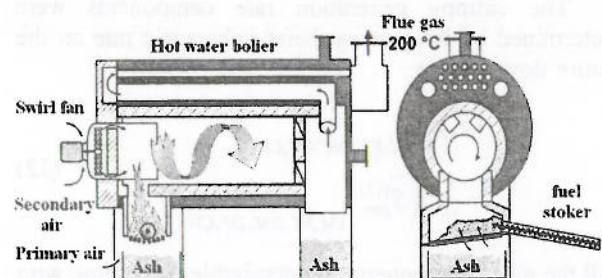


Fig. 1. Layout of the Pyrot combustion system manufactured by the company KÖB.



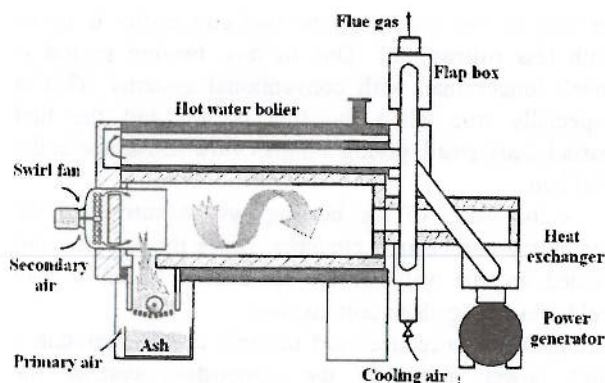


Fig. 2. Pyrot furnace with integrated Stirling engine TEK 40.

Two operation modes are possible:

**Regular operation mode:** The flue gas leaves the secondary combustion chamber and is directed via a line duct to the heat exchanger of the Stirling. It enters this heat exchanger and flows through the tube bundles of the heat exchanger to the outer gas collection vessel. The hereby cooled flue gas is directed via a transversal tube to the hot water boiler of the combustion system.

**Bypass mode:** In this operation mode the tube which directs the flue gases downstream the boiler to the stack is blocked by a flap. This is the same flap which blocks in regular operation mode the bypass tube. The hot gases are now sucked into a mixing chamber directly downstream the secondary combustion chamber. They are mixed with cooling air and directed to the stack via the flap box. Therefore, the flue gas flow in the stack is much higher than in regular operation mode. The system is able to produce an electrical output of 20 to 25 kW, provided that the fuel is suitable and the heat exchanger is not heavily dirty. However, the installed system is still suffering from some problems related to the use of the fuel wood chips which is more problematic than the fuel natural gas.

## OPERATIONAL PROBLEMS OF THE KRAILLING INSTALLATION

In the first period of the project, the object was to fully understand the problems of the existing technology. This is the base for further improvements of the system towards a better reliability.

### Fouling and slagging

The most crucial problem for Stirling engines fuelled with biomass is fouling and slagging. This problem is well known in all biomass CHP plants, not only in Stirling plants. Even if the content of particulate matter in the combustion chamber is reduced considerably like in the Pyrot furnace the problem still occurs and there is a need for cleaning the heat exchanger. There are two major types of fouling:

- **Deposition of particulate solid particles of matter (PM):** provided that the burn out in the combustion system is complete, PM in the hot

combustion gas derives from ash entrained by the primary. The inertia of the PM is higher than that of gas, depending on particle size and particle mass. Due to this, the PM impacts on the heat exchanger tubes when the hot flue gases flow through the heat exchanger. Influenced by the stickiness and the morphology of the particles they form a fouling layer which grows during operation. The content of PM depends on the combustion system and on the fuel type (wood chips or sawdust). Typical values are 1-2 g/m<sup>3</sup> for grate firings and 0,5-1 g/m<sup>3</sup> for underfeed stoker firings. The Pyrot furnace is designed to reduce PM content in the combustion zone. Therefore PM concentrations of around 100 mg/m<sup>3</sup> and below are typical values for this type of combustion system.

First measurements downstream the Krailling system showed concentration below 50 mg/m<sup>3</sup> when burning wood pellets. Next table gives an overview of these measurements.

Start	Stop	PM-concentration in mg/m <sup>3</sup>
11:11	11:21	42,35
14:00	14:10	31,06
14:58	15:08	34,56
15:32	15:42	32,80

Comparable values were found at a similar combustion system without Stirling CHP. This demonstrates that the combustion system chosen in Krailling offers considerable advantages in terms of low PM concentration and therefore reduced fouling by particle deposition. The oxygen concentration in the stack during the measurements was approx. 7% O<sub>2</sub>.

- **Condensation of volatile alkali:** Biomass fuels are rich in alkali like K and Ca. The alkali, like K and Ca, of the biomass fuel react during combustion with Cl or S forming volatile components like KCl or CaCl<sub>2</sub> or corresponding sulfates. When the temperature of the gas decreases, they condense and freeze on the surface of a boiler and the heat exchanger of a Stirling engine (temperature of the surface approx. 800 °C). The boiler condensation is not severe. It grows slowly and is not sticky so that the surface is readily cleaned. Due to the low temperature of the wall the temperature of the gas in the surrounding boundary layer is also low. Condensation and perhaps freezing may start before the particle hits the wall. At the latest the particle grow stiff on the surface.

The condensation on the surface of the heat exchanger is of different nature. The emerging coating grows fast enough to reduce engine power after some hours running. During operation, the condensate is expected to be of liquid state forming a mushy, sticking layer with the impacting particles. At the current temperature level, this fouling by condensation can not be avoided completely. It depends on the composition



of the fuel, where straw or other "young" biomass fuels are more crucial. One possibility to reduce the content of such volatile alkali in the flue gas is to inject additives with the biomass fuel. However, such additives are costly and it is questionable whether they can eliminate the problem completely.

Whereas the deposition of PM typically occurs where the PM impacts on the tubes, which means on the front side of the tubes directed to the hot gases, the condensation occurs when the gases cool down. Therefore, the condensed deposits can be found all around the tubes and it depends on the temperature level where most of the condensation takes place. However, one can not divide the different phenomena completely, as condensation phenomena also takes place on the surface of the particles.

However, the fouling rate which describes the growth of the fouling layer over the time is influenced by some factors:

- *Design of the heat exchanger:* The design influences primarily the deposition of PM, whereas it has minor influence on condensation phenomena. By reducing the surface area directly facing towards the flue gas stream, the risk of impaction of the particles can be reduced. A more streamlined heat exchanger therefore reduces the deposition of particulate matter. Additionally the pitch between the tubes and fins should be large enough to avoid plugging.

- *The temperature of exchanger tubes:* On the boiler surface the condensate is in solid state, on the heat exchanger it is liquid. With further increase of the temperature of the wall, condensation may be avoided. The role of the start up phase has to be examined separately. During this period, the surface is still cold and the high concentration of particles in the start phase may lead to a high fouling rate for a short time.

- *The type of fuel:* The important parameters influencing fouling and slagging are the content of K, Ca, Cl, and S in the fuel. Furthermore the particle size of the fuel influences the concentration of PM in the flue gas as the risk of entrainment, especially in grate firings, is higher if the fuel particles are smaller.

- *Start up of the CHP system:* The Krailling CHP system, shown in figure 2, is not optimized in terms of start up behavior and fuel flexibility:

- a) - the grate is small, so:
  - it lacks a zone for drying the fuel
  - that the velocity of the primary air is not as low as possible to reduce the content of particles in the flue gas
- b) - two problems are emerging from the fact that during start up, the boiler heat exchangers are bypassed completely:

- to avoid overheating of the chimney the flue gas fan has to suck not only the combustion gases but also additional cooling air. As the cooling air is sucked into the system directly downstream the combustion chamber, the pressure drop in the combustion chamber decreases. Therefore, less primary air can be sucked into the combustion system. This is unfavorable during the

start up of the system as the fuel conversion is lower with less primary air. Due to this, heating period is much longer than with conventional systems. This is especially true when the fuel is wet and the fuel particles are small, giving a higher flow resistance in the fuel bed.

- the water of the heating system surrounds the secondary combustion chamber. Since the water is not heated up, the walls of the combustion chamber stay cold preventing clean combustion.

In order to reduce start up time and to maintain a high power output of the combustion system, the requirements of the Krailling CHP system for the fuel are quite stringent. The fuel has to be dry and homogeneous. Best experiences were achieved with pellet fuels. However, one should keep in mind that pellets are expensive and combustion temperatures in the primary zone are considerable higher with this precious fuel. Furthermore, higher temperatures may give rise to a higher wear of the lining of the combustion chamber.

- *Fuel quality:* The influence of the fuel quality was already mentioned in the previous chapter. This chapter gives some additional comments concerning the fuel moisture. Next table shows the analysis of the fuel used during the combustion test.

Fuel type	wood chips	wood pellets
<b>Heating value</b>		
H <sub>0</sub> (MJ/kg)	12,43	18,75
H <sub>u</sub> (MJ/kg)	10,59	17,31
<b>Fuel composition</b>		
H <sub>2</sub> O %	38,6	8,1
Ash % (550 °C)	0,7	< 0,05
C %	31,08	46,75
S %	0,00	0,00
H %	4,11	7,99
N %	0,06	0,13
Cl %	0,01	0,01
O %	25,49	40,12
Volatiles %	49,70	78,23
Fixed C	11,04	17,38

The wood chips used during the first tests had a much higher humidity and, therefore, a much lower heating value than the pellets used during the last tests. A higher humidity of the fuel requires more primary air to burn the fuel. Furthermore, the reduced heating value due to the higher water content decreases the combustion temperature. Both problems reduce the fuel flexibility and it should be kept in mind that especially small combustion systems are very sensitive on higher fuel moisture. This is due to the higher surface/volume ratio of their combustion chambers and the hereby derived higher energy losses compared to larger combustion systems. Therefore, the manufacturers of small scale combustion systems limit the acceptable fuel moisture. The upper limit is 40% H<sub>2</sub>O. Forrest wood chips which were used in this facility during the



combustion tests are less suitable for the combustion system as they have water content near this upper limit. If one does not want to accept this limitation, additional techniques like flue gas recirculation or air preheating are required.

### RESULT OF THE MEASUREMENTS AT THE KRAILLING CHP PLANT

Before we took off the design of a new facility we investigated the operation of the Krailling CHP demonstration facility. Some results of the test, which were done with the fuels described in previous table, will be shown here.

Figure 3 and 4 shows the hot gas temperature, the temperature of the return water flow the heating system and the electrical power output of the Stirling engine.

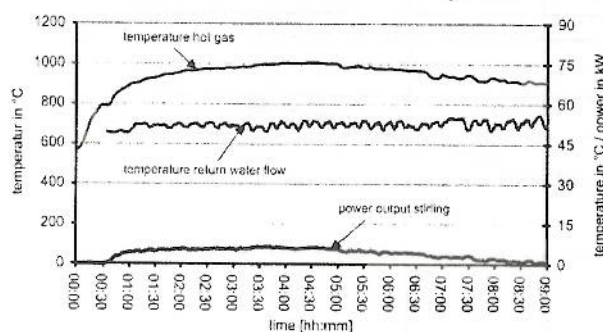


Fig. 3. Start up and operational behavior of Stirling engine with the fuel forest wood chips.

The system normally is fed with wood chips (water content of nearly 40%). In the first test (fig. 1) the heat exchanger suffered from a lot of fouling. Additionally the temperature of the hot gas was low, maximum temperature was 1000°C. Due to these influences the electrical efficiency of the Stirling engine was considered low. A positive result was constant low temperature of the return water flow from the heating system. This showed that the modifications in the heating system were successful.

After this test it was decided to clean the heat exchanger and to do another test with wood pellets. The system included an air pulse system to clean the tubes of the heat exchanger which proved to be not effective. We had to clean it with a knife, a wire brush and a sandblaster. Figure 2 shows the results of this test in a similar diagram. During this trial, the hot gas temperature rose up to nearly 1100°C which is the design temperature of the system. Together with the better efficiency of the heat exchanger, the electrical power output of the Stirling during the start up phase was much better. However, instead of a further increased efficiency the electrical power output got stationary at about 20 kW, even through the temperature of the hot gases increased. This was due to an increase in the return water flow temperature.

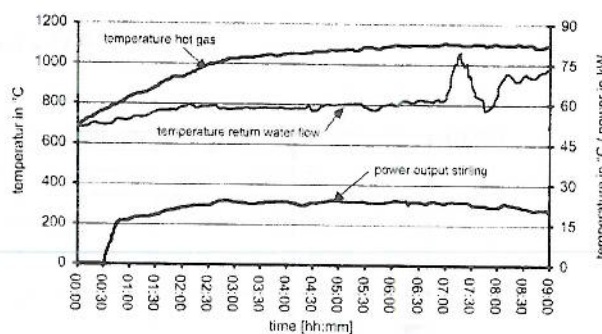


Fig. 4. Start up and operational behavior of Stirling engine with the fuel wood pellets

The two tests give only a brief impression of the real situation, but some basic conclusion can already be drawn:

- the hot flue gas temperature has to be maintained clearly above 1000°C in order to achieve a sufficient efficiency of the overall system;
- the Stirling cooling system is not sufficient to enable effective Stirling operation;
- the main hurdle that has to be taken is the fouling of the heat exchanger which has to be kept clean, the installed air pulse system is not sufficient.

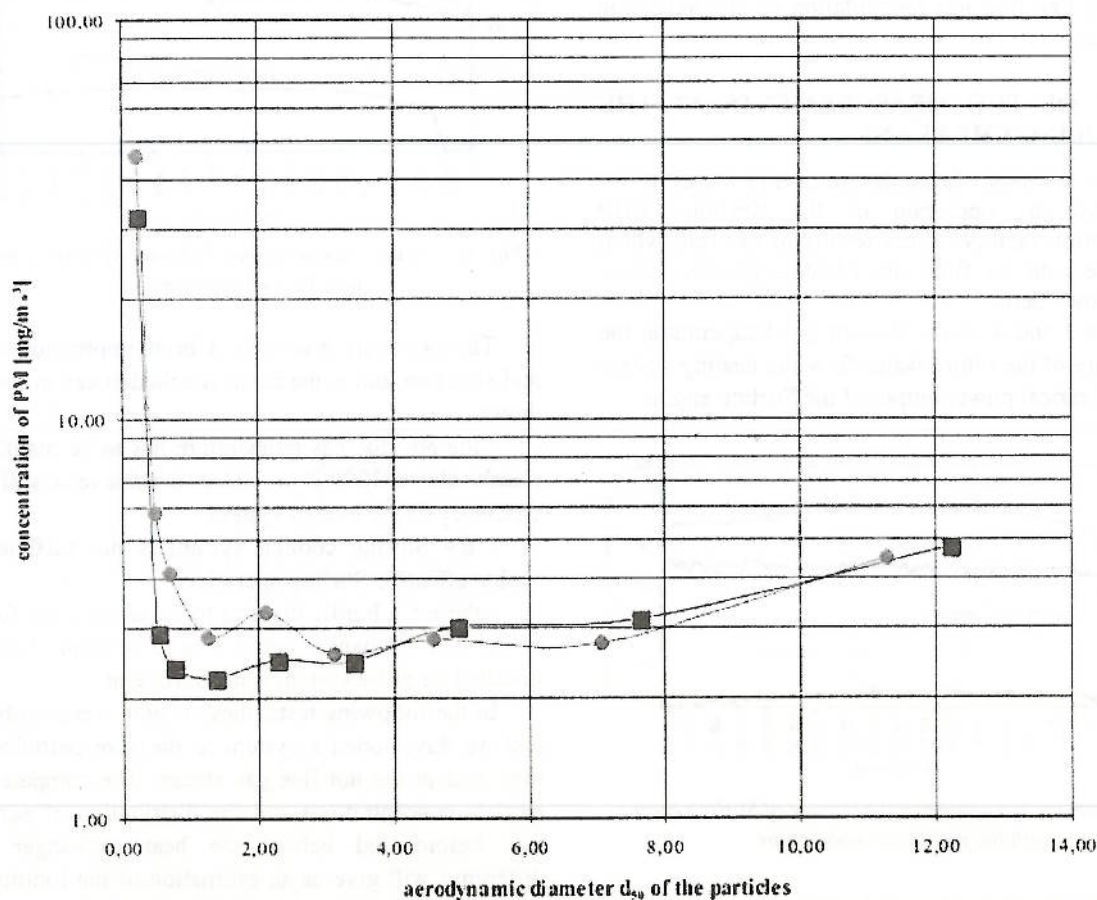
In the following tests, these results were confirmed and we developed a system to measure particles and their size in the hot flue gas stream. We compared the particle concentrations and the distribution of particles size before and behind the heat exchanger. The difference will give us an estimation of the fouling due to impact of particles. The PM concentration shown in previous table has been measured in the chimney at a temperature of 150–200°C. The filters of an Anderson Impactor, which was the basis for our measurements, can not stand much higher temperatures. So the flue gas has to be cooled down in a controlled way, making sure that condensation of vapor on the filters is avoided. All other condensing substances are supposed to condense before reaching filters.

One result is shown in figure 3. It can be expected that the total concentration of PM behind the combustion chamber is slightly decreasing overtime. Thus the red curve with the circled dots is supposed to be pushed to some less high values compared to the blue curve (squared dots). It can be seen clearly that most of the particles are very small. This had to be expected and made clear that use of a cyclone would not be effective. Since the relation between centrifugal force and frictional forces at the surface of the particles increases with diameter, a higher difference between the two curves had been expected at larger diameters.

Although different measurements at different times and place with varying flue gas temperature show a considerable correspondence, it must be said clearly that until now, we have only little proof for the exactness of the measurement at high temperatures.



## PM - concentration



	Total concentration	temperature	From	To	
Impactor before	74.34 mg/mm <sup>3</sup>	860 °C	18:40	19:10	red(o)
Impactor behind	55.98 mg/mm <sup>3</sup>	550 °C	17:32	18:08	blue( )

Fig. 5. Concentration and size distribution of PM before entering and after leaving the heat exchanger, firing with wood chips

## DESIGN OF A TEST FACILITY FOR AN IMPROVED STIRLING CHP SYSTEM

The main task was to design and to build up a new test facility which avoids most of the problems of the Krailling plant.

The objectives that have guided the design and the items which will be realized are:

1) Fuel flexibility (humidity), reducing start up period, raising the flue gas temperature or keeping the high flue gas temperature in part load, achieved by:

- extended primary combustion chamber with larger grate;

- no bypassing of the complete boiler;

- flue gas recirculation (injecting hot air will also be possible);

- together with a separate flue gas fan, this makes it possible to reduce the primary air share towards more secondary air thus increasing the temperature in the secondary chamber.

2) Minimizing of condensation:

- preheating of the complete system step by step by the flue gases;

- preheating of the heater head (externally).

3) analysis of fouling and slagging over time

- the intention first was to integrate the heater head of the Stirling engine in our test facility.

Meanwhile we modified that and have designed a heat exchanger for testing purposes that is divided in partitions allowing replacing single sections during operation.

With this improved CHP scheme, tests under lab scale conditions shall be applied. The test facility is coupled to a cooling system enabling constant operating conditions in terms of boiler load and cooling water temperature. The tests will focus on an improved temperature control system maintaining high temperatures in the secondary combustion chamber and on developing a suitable cleaning system for the heat exchanger (fig. 6).

Based on these results and on the next measurements, guidelines for improved Biomass/Stirling CHP system will be developed.

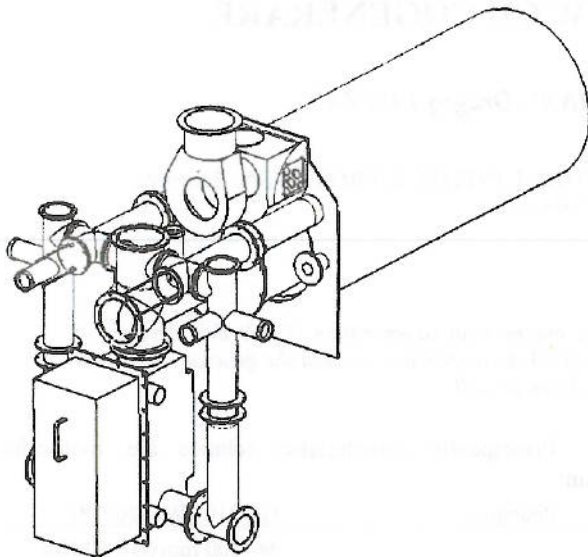


Fig. 6. Isometric view of the modified Pyrot furnace built up in the test site.

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COFRET



## 1<sup>re</sup> Annonce

Troisième Edition du  
**COLLOQUE FRANCO - ROUMAIN SUR  
 ÉNERGIE – ENVIRONNEMENT – ÉCONOMIE  
 & THERMODYNAMIQUE (COFRET)**  
 Timișoara, Roumanie, 15-17 juin 2006

Pour suivre les premières éditions : COFRET'02, organisé en 25 – 27 Avril 2002, par la Chaire de Thermodynamique, Machines Thermiques et Installations Frigorifiques de l'Université „Politehnica” de Bucarest (UPB) et COFRET'04, organisé en 22 – 24 Avril 2004, par LEMTA, Groupe GESPE, Université „Henri Poincaré”, Nancy I (UHPN) et de l'Institut National Polytechnique de Lorraine (INPL), sous l'égide de la Société Française des Thermiciens (SFT) et de la Société Roumaine des Thermiciens (SRT) et l'appui de l'Agence De l'Environnement et de la Maîtrise de l'Énergie, France, nous proposons maintenant la mise en place de la troisième édition du COFRET.

Le succès des deux premières éditions nous donne le droit et nous oblige de continuer cette action qui doit faire apparaître en parallèle les recherches communes et des prolongements techniques et industriels. On recherchera un équilibre entre université et industrie (importance des aspects ÉCONOMIQUES).

Il apparaît aussi que ce colloque permettrait de prolonger l'action actuelle de l'ADEME traduite par SIENE, et renforcerait la dynamique du réseau formation recherche en cours d'émergence, ainsi que la relation université – industrie qui reste actuellement à développer conjointement.

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