

A STUDY OF AN USER AND ENVIRONMENTAL FRIENDLY STORED ENERGY BASED EPU/APU-SYSTEM FOR MILITARY AEROSPACE APPLICATIONS

Erik Prisell*, Jan Brandin**, Owe Lyrsell***

*FMV Defence Materiel Adm. Sweden, **University of Lund, ***LUTAB AB

Keywords: *emergency power, stored energy, hydrogen peroxide*

Abstract

Modern military multi-role combat aircraft need an emergency power system (EPS) or an emergency power unit (EPU) to maintain back-up power supply for all normal and degraded flight modes.

The reason for this requirement is that modern combat aircraft are designed with a built-in relaxed or negative stability. Inability of the Flight Control System to perform continuous, corrective control surface actuation, due to loss of power supply or other causes implies instantaneous departure with loss of A/C. An emergency power system needs to have a quick response and provide high power, electrical or hydraulic or combined, to a low weight and volume for considered time.

Different EPU systems have been tried over the years, hydrazine (monopropellant) driven turbines, compressed air and all-electric battery systems are dominating in existing applications. Gas generator systems however show advantages, but hydrazine for example is both toxic and carcinogenic.

The operation of coming electrical weapon demands short bursts of very high power. The requirement of power, from this emerging field of applications, is conveniently fulfilled by tailoring of the EPU/EPS systems approach. A small stored energy based system can also be the power source solution for electrical weapons in medium sized unmanned aerial vehicles, UAV's.

FMV has since 1999 performed a study of an EPU system based on stored energy together with a turbine system. A novel gas generator

system has been developed and demonstrated which is both user and environmental friendly. The work-performing gas is generated from catalytically enabled and supported combustion of medium concentration hydrogen peroxide and methanol. The concept was evaluated by performing a feasibility study in three phases between 1999 and 2007. This paper will present the work performed and the results from these three phases. The paper covers both the results from initial studies of different EPU system concepts/solutions and from the demonstrator programs of two turbine concepts where the second concept also incorporated a working novel hydrogen peroxide/methanol gas generator.

Specific focus will be given to this novel gas generator concept which operates with a mixture of medium concentration hydrogen peroxide and methanol. The hydrogen peroxide is catalytically decomposed into steam/water and free oxygen that are used to combust the added methanol by a combustion catalyst into a high temperature (~ 600 °C) working gas.

1 Introduction and background

In the beginning of the 1980's, FMV [The Defence Material Administration] on behalf of the Swedish Armed Forces, placed a contract on the IGJAS-group, where SAAB Aerospace was a key player, to develop a new multi-role fighter aircraft including prototypes and a small batch of production aircrafts.

Already from the beginning, an inherent feature of this A/C, subsequently named JAS39 Gripen, was the defined maneuverability enhancing configuration layout based on relaxed stability,

whereby however the flight control system always requires an un-interrupted supply of hydraulic and electric power. The program continued with IGJAS submitting RFQ's to relevant subcontractors/manufacturers of different subsystems including the Emergency Power System [EPS]. The obvious choice for the EPS was hydrazine, but when reviewed, it ended up being prohibited in Sweden due to toxic and carcinogenic qualities. It was suggested the bi-fuel combination gaseous oxygen – methanol by one subsystem supplier, and this system was accepted.

Due to stubborn problems in the development, this system was discarded at a late stage in the A/C type development program.

Due to smart design of the flight control system flight laws and a general effort to restrict power requirements, the anticipated maximum power level for the hydraulic system part of the EPS was around 5 kW, and the maximum requirement on duration was around 15 minutes. The simultaneous requirement on electrical power was even less. This resulted in a limited energy and power demand which opened up for a replacement of the original EPS system with an all-electric version. In the end, the production aircraft had the power and energy requirement fulfilled by a so called Thermal Battery. The hydraulic power is produced by a connected electro-hydraulic pump unit.

The problems with the original EPU system was a technical issue of a major concern to the IGJAS/SAAB as well as to FMV during the second part of the 1980's. Different studies were launched to find alternative technical solutions to the problem. The Swedish Bofors Underwater Division that develops and produces torpedoes for the Swedish Navy was approached. Swedish torpedoes are propelled by a bi-fuel combination of hydrogen peroxide of high concentration and a hydrocarbon fuel. This is of course also a sort of [non-breathing] EPS system, and the Swedish Navy has very good experiences from both using and handling this fuel combination. However, at this time this potential EPS was not further investigated.

Although an all-electrical system finally was chosen but it was always felt that an EPS system

based on a propellant-driven turbine exhibited certain advantages.

"COTS" and "Dual-Use" drive

During the 1990's it became obvious that the escalating development cost for military systems were becoming unacceptable. In line with the COTS[Commercial-off-the-Shelf] and Dual Use[combined cost-shared civil and military development] trend in the US, Sweden adopted a similar view.

The well-known Swedish producer of compressed-air driven hand-held tools, Atlas Copco, started during the 1990's to introduce efficient small turbines as the pneumatic motor in some of their products. As these products are produced and sold in large quantities with a correspondingly related market situation with low allowable price tags, a prerequisite for introducing turbines at all into this product segment is that a correspondingly low production cost can be established. This was finally achieved and towards the end of the 1990's, Atlas Copco had the capability to a cost-effective production of turbines in the smaller and medium sized series, up to typically 10,000 units.

Adjusted chemistry-configuration

Thermodynamic analysis pointed out that it might be possible to run a gas generator on a bi-fuel combination of a hydrogen peroxide/ water solution of medium concentration together with a conventional fuel. Such a fuel combination would significantly lessen the handling problem aspects of the hydrogen peroxide. Also the turbine inlet temperature would automatically fall into a decent range.

Aircraft platform perspective

- From an end-user A/C platform perspective, the feed-back from the initial Thermal Battery use in the Swedish fleet of JAS39 Gripen aircraft pointed to the nuisance of inadvertent firing of these batteries. The EPS system is critical, and is triggered on different combinations of sensor signals. This trigger level is set safe, meaning that the system is definitely triggered when function is called upon. The consequence is however a not insignificant probability of inadvertent firing, i.e. firing of the batteries although nothing was wrong with the

normal supply. The consequence has no harm, but the batteries are thereby consumed and must be replaced. These batteries are very expensive.

- The Thermal batteries can not be tested, (compare with the situation of testing matches). A testable system would be preferable
- Conceptual design of future UAV systems was also of interest.

FMV therefore decided in late 1998, to perform a feasibility study addressing the above described elements.

2 Phase I, Feasibility study

2.1 Definition of technical approach

LUTAB, a Swedish aerospace specialist and consultancy company was given the assignment to undertake a feasibility study with the purpose of identifying, and to some extent also quantify, relevant parameters of interest. This study was performed in collaboration with Atlas Copco, the producer of turbines for commercial hand tools.

In this initial study, a hydrogen peroxide, (H₂O₂), monopropellant system with a concentration of only 60%-by weight was chosen as a systems baseline. It was understood the that catalytic decomposition products resulting from this H₂O₂ concentration would contain a small fraction of liquid water, a fact not considered to be of any significant disadvantage in itself. However, this choice was done to allow for an unproblematic continuation into a possible demonstrator phase:

- 60% H₂O₂ is the upper limit for having a pretty unrestricted handling of this chemical
- The reaction chamber exhaust temperature is buffered by the water residue and will be equal to the boiling temperature at given pressure, allowing for use of COTS turbine samples.

For analytic system comparison purposes, the degree of freedom was given that either the H₂O₂ - concentration, or a an added fuel to be

combusted, or combinations of both, could be introduced.

2.2 EPU System evaluation approach

It was decided that a conceptual MEA[More-Electric-Aircraft] Basic Aircraft Sub-systems layout adapted to the requirements for an envisaged UAV/UCAV should form the applicatory example for this H₂O₂ EPU-system study in a possible EPS system.

Considering the complete EPU-system as a black box and as part of a MEA-system, you only need to consider the delivered electric power over time as the delivered utility, thereby simplifying the evaluation.

The generalized specification of the UCAV was as follows:

| | |
|-----------------|-----------------------------------|
| Empty weight | 4 [metric] tons |
| Fuel | 2 [metric] tons |
| Weapon load | 2 [metric] tons |
| Wing span | 5 – 6 meters |
| Max speed | < 1 Mach |
| Maneuverability | Limited |
| Other | Terrain following, low observable |

Table 1.UCAV generalized specification

Basic Aircraft Sub-systems to be managed by MEA:

- Flight Control Systems Electromechanical Actuators
- Landing gear retract/extend actuators
- A/C-battery
- Avionics
- Engine starter

The suggested and studied EPU-system was dimensioned against the resulting electric system load requirement profile and other relevant requirements. The studied EPU-system was then evaluated, primarily weight-wise, against two competing systems:

- Auxiliary and emergency system of “conventional” type made up by one APU and a thermal battery, and
- All-battery system split in 2 parts; one Ni-Cd rechargeable unit and one on-demand triggered one-shot thermal battery.

2.2 EPU System requirements

The analyzed system[s], [2], was actually configured to replace a complete AEPUS [auxiliary and emergency power system], whereby the essentials of the system requirements can be summarized as follows:

- To supply power for main engine start on ground
- To deliver electrical power supply in back-up, auxiliary and emergency mode for flying home and perform landing
- To supply power for restart of main engine after a flame-out in the air

Together with the general lay-out of UCAV and other assumptions, other significant requirements could be stipulated, as follows:

- Max power level 10 kW
- Mean power requirement 4 kW
- Duration 0,5 hours
- Start time less than 5 sec (an engine flame-out situation)

2.3 Results

The theoretical evaluation was primarily done by trying to define a systems “black box” for each one of the configurations, and that this “black box” contained all the specific parts that made the specific system unique. The weight of this “black box” was estimated for each system lay-out. The resulting weight differences reflect the system weight advantage/disadvantage.

The resulting system weights are tabled below.

| [A]EPU system configuration | Weight [kilogram] |
|--|-------------------|
| H ₂ O ₂ as covered by this feasibility study | 32 |
| Auxiliary and emergency system of “conventional” type | 29 |
| All-battery system | 58 |

Table 2. (A)EPU subsystem comparison

The different weights resulted from a balanced analysis with inputs scaled from actual existing systems. For the all-battery system, the figures were adjusted to energy densities as stated by contemporary and relevant literature sources; 30

Wh/kg for used NiCd and 40Wh/kg for Thermal batteries, [1].

Conclusions that could be drawn from the study were:

- The three systems exhibit a similar weight penalty, however the all-electrical system is somewhat heavier with at time available battery technology
- Due to inherent features of the systems lay-out, the “conventional type” system exhibits increased complexity and cost expectation and is also likely to require a larger installation envelope
- The hydrogen peroxide system as covered by this feasibility study exhibits certain interesting features, especially when a functionally robust, compact, non-complicated, environmental friendly and cost effective system is asked for.

2.4 Feasibility study; Phase I B

Following the encouraging results from the feasibility phase 1, it was decided to further specify the suggested system leading the way to a potential future airworthy and qualified H₂O₂ EPU-system.

This was done by launching a second part, part 1B of the feasibility study.

The primary purpose of phase 1B was to produce a draft specification for an EPU System Demonstrator as a required development step directly proceeding the actual Demonstrator hardware procurement phase.

Apart from configuring the system demonstrator to be in line with a future system prototype, it was also the purpose to identify technical and other risks to be anticipated in the further development program.

The outcome of this specification development phase addressed aspects such as:

- Mechanical and electric interfaces
- Test rig specification
- LRU (Line replaceable unit) / Subsystem component tests
- System tests specification
- Criteria for the evaluation process

3 Phase II; Demonstrator No 1

3.1 Introduction

A continuation of the study into a hardware demonstrator phase was decided by FMV after reviewing the results of the performed feasibility study. Atlas Copco then proposed a concept of a System demonstrator based on their commercial turbine and high speed generator technologies. A contract was placed in the fall of 2001 and the project was completed by end of June 2002. Unfortunately no subcontractor was to be found to be able to develop a gas generator system based on hydrogen peroxide as stored energy. Atlas Copco then suggested a system simulating the hydrogen peroxide gas generator based on a steam generator specially designed for the purpose. The total system including the steam generator went through a test and evaluation program at Atlas Copco, Thermo Dynamics Laboratory, in Nacka just outside Stockholm. The scope, build up, results and findings are described below.

3.2 Scope

The scope of the demonstrator program was to demonstrate a small power dense turbo/generator concept as a potential EPU system in the 6-7 kW electrical power range for a medium sized UAV. The scope was also to show the potential of the use of commercial turbine and high speed generator technologies then identified at Atlas Copco. The key components and subsystems to be validated were the turbine and generator functions together with the power capabilities of a complete unit. Other subsystems such as the electrical management and the electricity quality aspects were not covered in this study.

3.3 System description

Turbine

The turbine consisted of a 3-stages impulse turbine. The first two stages were made in a high yield strength stainless steel. The last stage was made in Titanium. The max turbine diameter was around 80 mm. The high pressure steam of 55 bars and around 640 °C entered in a partially open nozzle ring. In the last turbine stage provisions was also made to be able to have a bleed air capability as a possible additional solution for a potential serial application. All turbine stages have graphite tip seals. The possibilities to have covered blade tips were first considered but the stresses due to high speed and temperature became too high. The bearing arrangement consisted of three hybrid bearings with one bearing at the generator end and the other two in between the turbine stages. The design point was 6 kW+, at 85000 rpm with a 640 °C steam at 55 bars to a flow rate of 0,009 kg/sec.

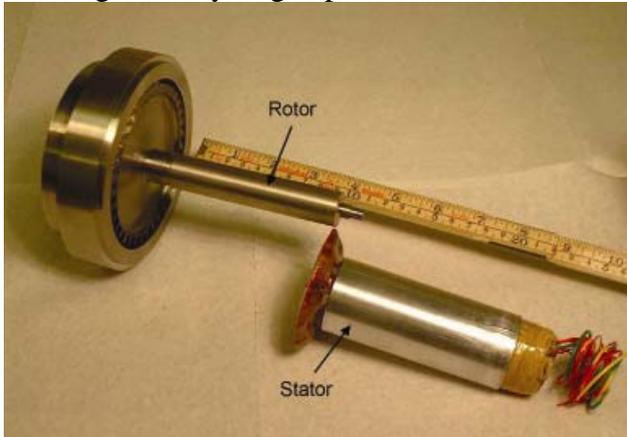


Picture 1. The Atlas Copco turbine rotor

Generator

The electrical generator design was a 3-phase system with powerful permanent magnets, (Neodymium), compressed on the turbine rotor shaft. The magnets were covered with a stainless steel sleeve for stiffness and containment. The stator consists of copper windings, 0,2 mm wires, and iron sheets. The generator design was of a, by Atlas Copco, patented design also used in other applications. The generator efficiency was predicted to 95% by 85000 rpm and the phase voltage of 115 V

per phase. This meant that heat of 30W had to be cooled off. A special water cooling system was then incorporated in the design. In a possible real application the water should be exchanged for hydrogen peroxide.



Picture 2. The electrical generator

Power module

The power module consisted of an integrated turbine/generator unit. The gas generator unit was a separate system and in a potential application it was thought to be adapted as a separate module. The third module also not included in this study would have been an electrical management and control module.

The power module can be seen below. The dimensions are maximum diameter 153 mm and length 200 mm.



Picture 3. The Atlas Copco power module

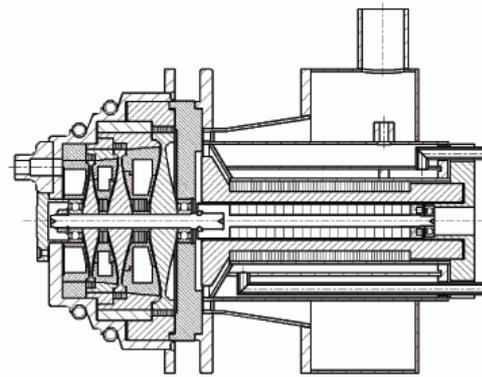
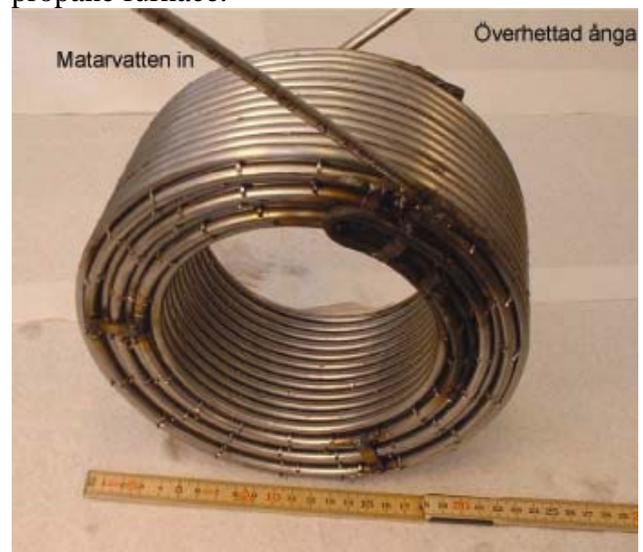


Figure 1. A cut through drawing of the power module. The turbine rotors to the left and the generator to the right

Boiler

The steam generator consisted of a coil boiler made out of a stainless steel tube 6 mm O.D and 4 mm I.D, 42 meters long wound in 7 layers. The water first enters the outer ring for pre heating before it goes to the inner rings. The boiler coil is vertically integrated in a ceramic propane furnace.



Picture 4.Boiler system

3.4 Test rig

An integrated test rig was developed including the power module and the steam generating plant. The water supply to the steam plant was provided with a compressed air system. The generated electrical power was converted to heat by the use of heat coils. The burner was manually controlled and the water supply was also manual controlled with the help

of a constant flow valve. The system scheme can be seen in the figure below.

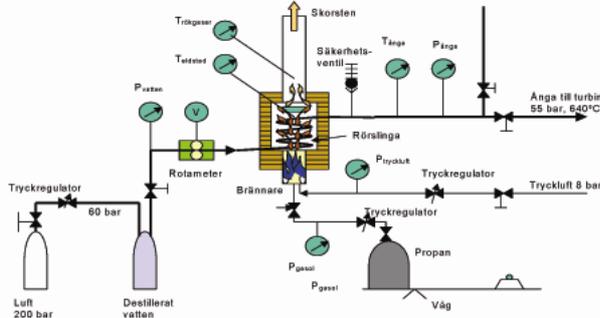
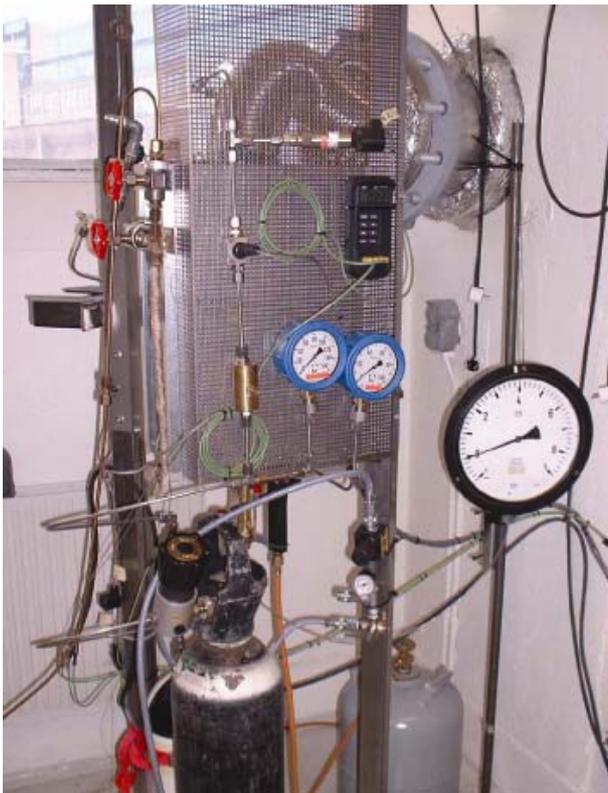


Figure 2. Test system schematic lay out

In the picture below of the test rig, the power module and the steam generator are located behind the perforated sheet metal.



Picture 5. Atlas Copco test rig assembly

3.4 Test program

Test programs was defined both for subsystem testing such as the steam generating system as well as for the complete system. The ability to control the water flow into the boiler was more difficult than anticipated. The

automatic water flow control didn't work as planned. Manual regulation was a necessity but it was difficult to keep the flow settings steady.

The whole test set up was instrumented by a dozen sensors for pressures, temperatures, frequencies, voltage, current etc. The sensors were connected to a data logger "Agilent" Type 34970. The data was sampled and processed in a PC system with the use of "Bench Link" software system. Beside the steam generated power a part of the testing was also done with the bleed air mode.

3.5 Results

General

Despite some problems such as steam generation and rotor dynamics it was possible to demonstrate a compact EPU system including a high speed generator in the 3-6 kW power class.

Power module

Due to the problems with the steam generation it was not possible to achieve more than a 3 kW output from the power module at a speed of 50000 rpm. The design speed was 85000 rpm and the specified calculated power at 85000 rpm was 6 kW. The reason for the lack of power was investigated but no root cause was found. One reason was believed to be that part of the steam did condensate in between the second and third turbine stage which could have caused a drastic loss in both efficiency and power. The generator function was however well above the specified power levels. The generator gave 6,7 kW tested in the bleed air mode at 64700 rpm. The bleed air, (10 bars), was only introduced on the last turbine stage. This was however a very good result as the turbine was designed for steam and not air. The turbine was not optimized for an air mode especially as the bleed air in the test was cold air (20 °C), compared to a real application, (engine bleed).

A summary of test data is presented in table 3 below, calculated data under "Spec".

| | Spec. | Steam | Bleed air |
|-------------------|--------|-------|-----------|
| Mass flow(kg/sec) | 0,009 | 0,009 | 0,075 |
| Speed (rpm) | 85 000 | 50000 | 64700 |
| Power module eff. | 0,65 | 0,35 | 0,49 |
| Generator eff. | 0,95 | | |
| Power (kW) | 7 | 3 | 6,7 |

Table 3. Test data from Atlas Copco,[3].

3.6 Findings and summary phase II

Rotor dynamic problems occurred at the end of the test program which resulted in a damaged shaft and tip rubbing of the turbine wheels. Lack of funding at this late stage made the program to come to an end. The demonstrator program had however shown that a small turbine based 6 kW power class EPU system can be developed. The generator design had specifically shown a potential well above 6 kW at high efficiency > 90% to a very low weight and volume. The program was therefore looked upon as a success even with the experienced turbine problems and the lack of a hydrogen peroxide system. Other lessons learned without fully understanding the lack of power was the scaling down effects of a high pressure steam turbine. These effects might have bigger impacts of the efficiencies and the predicted power outputs than anticipated. The Atlas Copco demonstrator program was finalized in a report, [3].

4 Phase III; Demonstrator No 2

4.1 Introduction

The results of the Atlas Copco project were despite the experienced problems intriguing. With new funding FMV started to investigate a possible third phase where focus was going to be the hydrogen peroxide system. At this time, around 2004, FMV had been in contact with a specialist company Catator AB in southern Sweden. This company was specialized in catalytic combustion and catalytic materials. They were interested to participate in a study of a hydrogen peroxide gas generator. The first step however was to put a small contract with Catator to do a feasibility study and develop a micro scale gas generator as

proof of concept before any further activities were going to be taken.

The level and effort in this planned third phase was thoroughly investigated in parallel at FMV. Different approaches, a total of five different projects, were studied. One approach was to repair the Atlas Copco system, another to develop a hydrogen peroxide gas generator demonstrator and demonstrate on an existing JAS 39 Gripen EPU system. The more lean approach was to continue with only a paper study. To continue the Atlas Copco project by repairing the unit and include a gas generator system might have been the most feasible approach. But unfortunately at this time Atlas Copco had moved the whole Thermo Dynamic Lab facility to Belgium and on top of that, the chief designer involved in the project was now also retired. To have somebody else involved and start all over with this approach was then looked upon as a high risk program.

The final choice became a low to medium risk approach where a small turbine unit was going to be designed for a low pressure < 10 bars system but still big enough to demonstrated a power capability in the 4-6 kW range. Instead of using a generator the power was going to be absorbed by a load compressor. A small high speed generator was already successfully demonstrated in the Atlas Copco project why the focus here was intended to demonstrate a stored energy system based on a medium grade hydrogen peroxide system sufficient to provide ~ 4-6 kW power. The power module including the test rig assembly design was contracted to Swekon AB in Stockholm with the support in turbine design by KTH ,[Royal Institute of Technology] ,Heat & Power.

4.2 Hydrogen peroxide

Hydrogen peroxide, H_2O_2 , is a colorless liquid mixable with water in any proportions. It can easily be decomposed into water and oxygen by the use of a catalyst:



The decomposition is exothermic (-50.7 kJ/mol), and a decomposition of concentrated

hydrogen peroxide can produce temperatures of several hundred degrees together with massive pressure build up. Due to its ability to rapid production of hot gas from an ambient temperature liquid, concentrated (>70 mass %) hydrogen peroxide have been used as a mono-propellant in the past. However, since the produced gas will contain oxygen, it is also possible to use this gas as an oxidizer for a fuel in a bi-propellant system and thereby gaining performance like increased power outtake or improved range.

If the hydrogen peroxide concentration is below 70 mass%, the heat of decomposition is not sufficient to evaporate the entire liquid bulk of the hydrogen peroxide-water mixture. This means that the maximum achievable temperature is equal with the boiling point of the liquid, mainly water at the end of the decomposition. This makes the decomposition much less vigorous than in the case of concentrated hydrogen peroxide. Stabilized hydrogen peroxide below 70 w % is sold as technical grade and is considered to be relatively safe to handle. This also means that the diluted hydrogen peroxide solution is rather useless as a mono propellant. However, if the missing heat, required to evaporate the whole liquid bulk, is supplied in the form of an external fuel to be combusted by the formed oxygen, a more potent bi-propellant system has been created from the diluted hydrogen peroxide solution. It is, however, not without a risk to mix hydrogen peroxide, even if it is diluted, with a fuel.

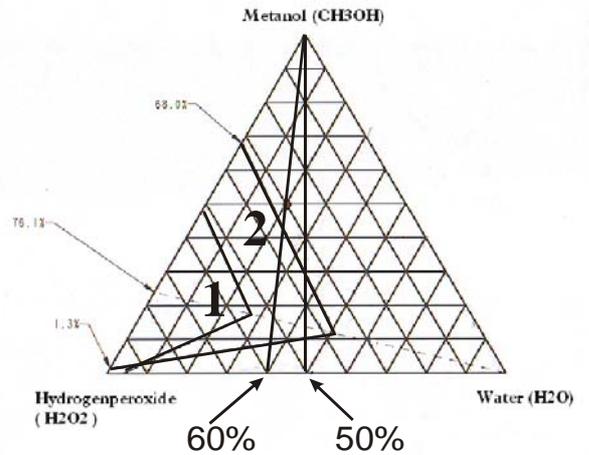
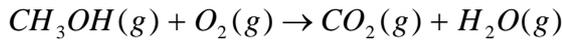


Figure 3. Triangular diagram over the H₂O₂-H₂O-methanol system. 1) instable system, 2) requires initiator, [5].

In figure 3 a triangular diagram is given over the H₂O₂-H₂O -methanol system is given in [5]. There are two areas denoted 1 and 2. Mixtures in the first area are unstable and may detonate if subjected to vibrations, shock or heat. In area 2, the system is safer but can be brought to detonate with the help of an initiator. Outside area 1 and 2 the system is considered safe to handle. There are two points marked 60% and 50% on the hydrogen peroxide-water axis. Those are the starting points and the lines describes the paths the mixture follows when starting to adding 100% methanol into 60 respective 50% hydrogen peroxide. As can be seen from the diagram, it does not matter in what ratios the diluted hydrogen peroxide (50 and 60%) is mixed with the methanol, it will never enter the area 1 region.

4.3 Chemical Reaction System

As stated above, the hydrogen peroxide decomposes when it comes into contact with a suitable catalyst into water and oxygen. Due to the evolved heat of reaction eventual added fuel is vaporized if it is sufficient volatile. In this project the used fuel has been methanol that vaporizes easier than water. The formed gas, containing oxygen, methanol and steam, then passes over a combustion catalyst that oxidizes the methanol:



The combustion reaction is exothermic and releases $\Delta H_c = -671$ kJ/mol. The temperature increase of the gas depends on the added amount of methanol, in figure 4 and 5, the adiabatic temperature in the formed gas is calculated as a function of the added amount of methanol, with the assumption that the gas composition reaches equilibrium at the obtained temperature. The peak value of the temperature curve corresponds to the stoichiometric point, where there is sufficient with oxygen to combust all the methanol. Left side of the peak in the figure corresponds to mixtures where oxygen is in excess over the fuel; lean mixtures. The right side of the peak corresponds to mixtures where the fuel is in excess over the oxygen; rich mixtures. When rich mixtures are used, unburned fuel will pass out from the reactor. This can also be seen in figure 4 and 5 where the low heating value (LHV, heat of combustion at 25 °C) of the outlet gas is calculated.

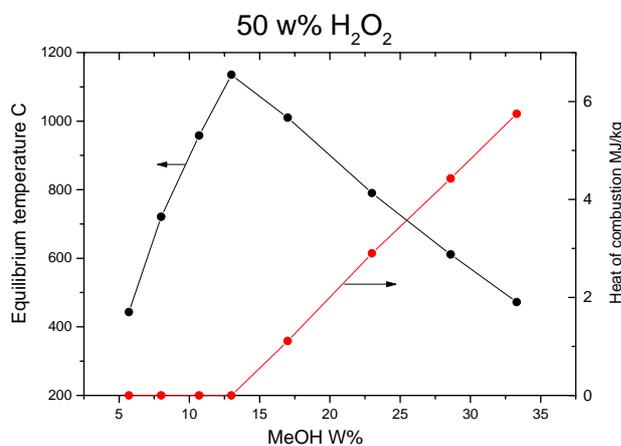


Figure 4. Adiabatic temperature and LHV in the formed gas versus added amount of methanol to 50 % H₂O₂

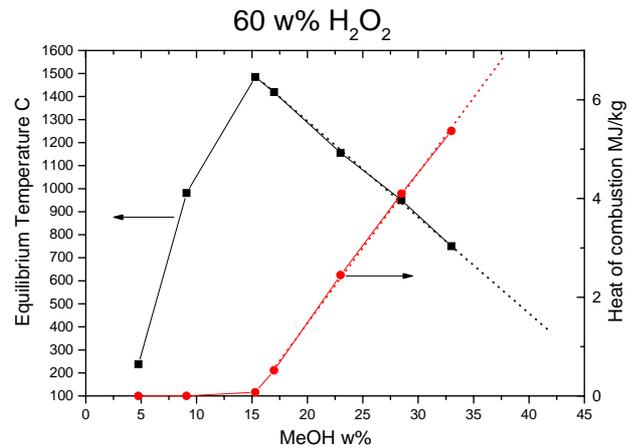
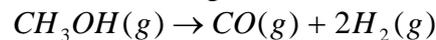


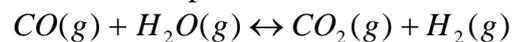
Figure 5. Adiabatic temperature and LHV in the formed gas versus added amount of methanol to 60 % H₂O₂

However, it is not unburned methanol that passes out. With a suitable catalyst and sufficiently high temperature in the gas, the methanol is decomposed in a chemical reaction called reforming:



This reaction is endothermic (90.5 kJ/mol) i.e. it binds heat. The more methanol that reacts according to this path, the lower temperature in the reactor.

In parallel to the combustion and the reforming reactions the water gas shift (WGS) reaction will also take place:



This reaction is ruled by equilibrium and the equilibrium state depends on temperature and initial gas composition. If a large excess of water is present, the reaction is pushed to the right. This means that the major components of the gas leaving the system are H₂O, CO, CO₂ and H₂. In figure 6 and 7, the equilibrium gas phase composition has been calculated as a function of the added amount of methanol (MeOH) for 50 % and 60 % H₂O₂.

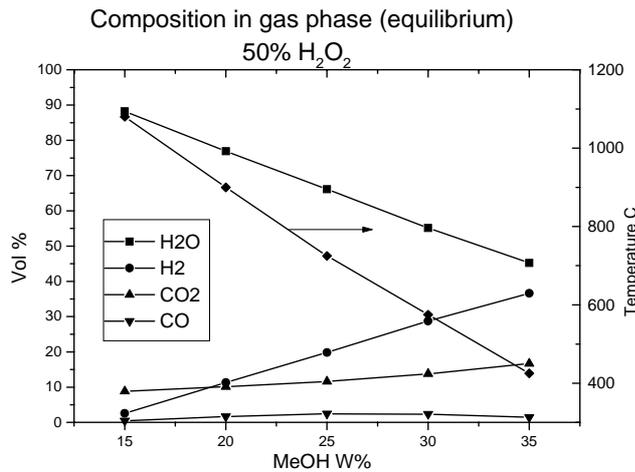


Figure 6. Equilibrium gas phase composition as a function of added amounts of methanol to 50 % H₂O₂ at adiabatic conditions. (Corresponding temperature marked with an arrow read to the right).

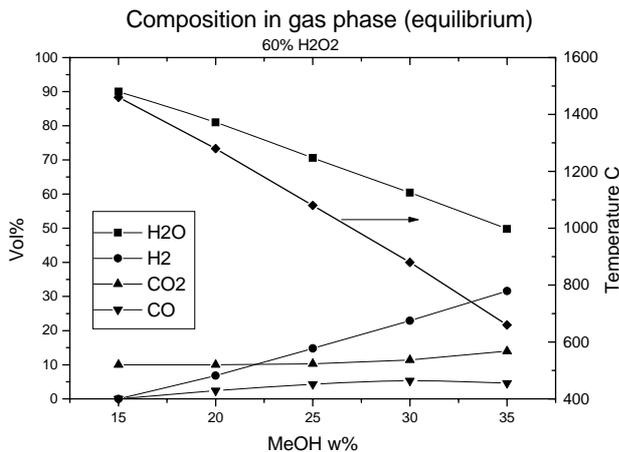


Figure 7. Equilibrium gas phase composition as a function of added amounts of methanol to 60 % H₂O₂ at adiabatic conditions. (Corresponding temperature marked with an arrow read to the right).

4.3.1 Micro scale reactor; Proof of concept

The main problem that arises from using diluted hydrogen peroxide solution as the oxidizer in a bi-propellant is to initialize and maintain the reaction. The stored chemical heat in the mixture (H₂O₂/water + fuel) can be sufficient to evaporate all of the liquid and rise the gas temperature several hundred degrees but the reactions does not occur spontaneous when the two liquids are mixed at ambient temperature. If

the liquid mixture comes into contact with a H₂O₂ decomposition catalyst, the H₂O₂ decompose into water and oxygen and will increase the temperature of the liquid to the boiling point, but there will not be any noticeable reaction between the fuel and the formed oxygen in the liquid phase. The gas formed will contain oxygen, water and fuel. The ratio between fuel and water depends on the size of the heat of vaporization for the each component, and if a fuel with low heat of vaporization, compared to water, for instance methanol is chosen, an enrichment of methanol in the gas phase occurs, compared with the liquid phase. If this gas comes into contact with a combustion catalyst, (for instance Pt/Al₂O₃) with high surface area (150 m²/g) at a temperature of 110 C or slightly over the boiling point of water (1bar), the gas mixture will ignite and combust on the catalyst surface. This means that the heat of combustion is released in a different place from were the decomposition/vaporization takes place. Since there is a lack of heat in the vaporization step a part of the combustion heat must be transferred to the vaporization step to make the process work continuously.

4.3.2 System

The first working continuous prototype, with a capacity of 1 g/s, in this project utilized a separate decomposition/boiler chamber and a separate combustion reactor. The hot outgoing gas was heat exchanged with the cold incoming liquid flow in an external heat exchanger. This first design was not considered possible to scale up in a rational way and was abandon. Based on the knowledge learn from the first prototype a second one was constructed, figure 8. The gas generator, with a capacity of 1 g/s consists of a 100 mm long tube, 30 mm in OD, in stainless steal

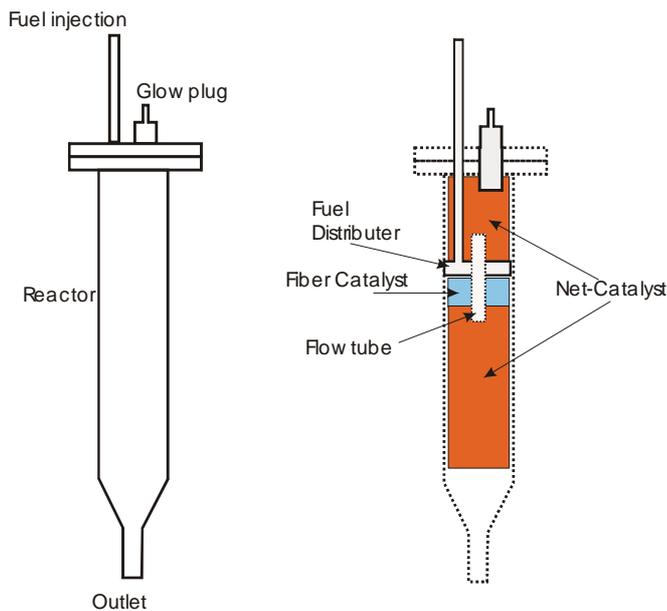


Figure 8. Micro reactor

The tube is divided into an upper and a lower chamber filled with net-catalyst [6], (wire-mesh a Catator AB's hydrogen peroxide decomposition catalyst). The active phase was Pt supported on alumina. The two compartments were separated by a plug of fiber catalyst with Pt as active phase. The fiber catalyst was produced at Catator for this project. Just above the fiber catalyst, a ring-shaped fuel distributor is located feed by an inlet tub.

To start the gas generator the glow plug is lit, heating the catalyst in the top layer. When the fuel (diluted H_2O_2 + methanol) is injected, it will be distributed over the fiber catalyst and gas starts to develop. When the fiber catalyst get wet, the pressure drop across it becomes high. The gas, trying to escape the chamber, goes up and out via the flow tube. Doing this, the gas passes the hot area in vicinity of the glow plug, and ignites. In this way the gas have a circulating movement and transfers a part of the heat from the combustion to the vaporization step. When the gas generator has started up, the glow plug can be disconnected.

4.3.3 Tests and results from the 1 g/s prototypes

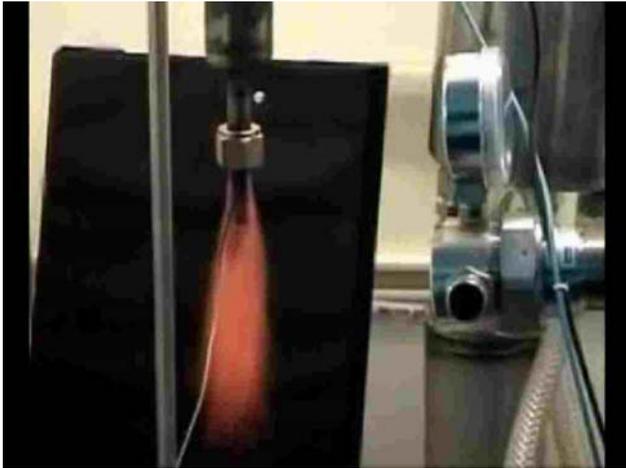
For the 1 g/s micro scale reactor premixed methanol –hydrogen peroxide solutions (50 and

60 %) were used. The mixtures were chosen outside the area 2 in figure 3, on the safe side. For instance 30 w % methanol in H_2O_2 (50 %) resides just on the border line (figure.3) and should (in equilibrium) produce a gas temperature of just below 600°C (figure 6).

The first of the 1 g/s prototypes demonstrated continuous auto thermal operation but was slow in response and startup.

The second prototype (figure 8) also demonstrated a fast and reliable startup and a fast response on load changes (premixed fuel). However, to obtain a good operation the fuel mixture should have a composition close to the area 2 border in figure 3. Stable operation at increased pressure, up to 10 bars, was also demonstrated.

Findings from the tests were that fuel mixtures on the lean side deactivated the catalyst quickly (could be complete in 60 seconds). Fuel mixtures on the rich side did not show this impact on the catalyst. The reason for this, is suspected, to lay in the above described reaction behavior of fuel mixtures. Due to the difference in heat of vaporization between methanol and water, the produced gas from the decomposition will be enriched in methanol in comparison with the liquid. On the lean side, there is an excess of oxygen compared to the fuel. When this mixture burns, higher temperatures are produced than given by the equilibrium calculations, since a large part of the liquid still remains. This leads a overheating and deactivation of the catalyst. On the rich side, there is instead an excess of fuel. When the temperature increases, the remaining unburned fuel starts to react according to reforming reaction described above. The reaction is endothermic, it binds heat. This prevents the catalyst from becoming overheated. In other words: The excess fuel acts as a thermal break in rich mixtures.



Picture 6. Burning produced gas in a rich fuel mixture experiment.

| Component | MeOH 33 w % | MeOH 27 w % |
|--------------------------|-------------------|----------------|
| H ₂ O (mol %) | 49.5 | 62 |
| H ₂ (mol %) | 33 | 23 |
| CO ₂ (mol %) | 15 | 12.4 |
| CO (mol %) | 2.4 | 2.5 |
| LHV MJ/kg | 5.2 | 3.5 |
| Adiabatic Temp °C | 600 | 753 |
| Measured Temp °C | 550 | 670 |

Table 4. Calculated equilibrium composition with 50% H₂O₂ , calculated and measured temperatures

4.4 Full scale reactor

For the demonstrator, a “full scale” prototype with a capacity of 20 g/s was constructed. As a base for the scale-up, constant flow rate per cross section area was chosen. This means that the length of the gas generator (catalyst bed) was constant while the diameter was increased. The number of flow tubes was also increased proportionally to the increase in flow.

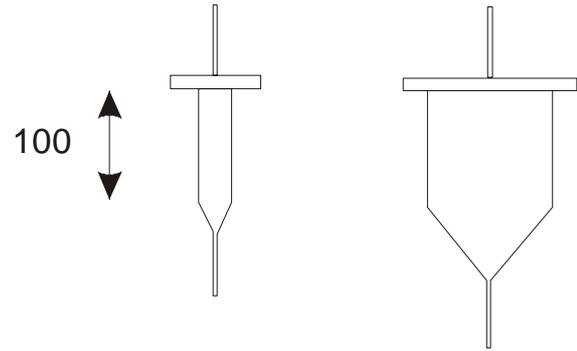


Figure 9. The 1g/s prototype to the left and the 20 g/s prototype to the right.



Picture 7. Assembling of the full scale gas generator.

4.4.1 System

Previous, in the small scale experiments premixed methanol-hydrogen peroxide solutions was used as fuel. To increase the safety, the methanol and hydrogen peroxide was now separated into two different pressurized vessels. To feed the gas generator, two mass flow regulators was used, one for methanol and one for the hydrogen peroxide. The controller for the mass flow regulator kept the mass ratio between methanol and hydrogen peroxide constant (adjustable set point) during the operation. With this control (master-slave) it was possible to freely vary the load at constant mixing ratio or changing the power (by adjusting the ratio) at constant mass flux.

4.4.2 Test program

Before integrating the gas generator into the full system, it was tested at atmospheric conditions and pressurized up to 5 bars. Both 50 % and 60 % hydrogen peroxide was used in tests.



Picture 8. Test run of the standalone gas generator. Insulated with ceramic wool to reduce the heat losses

In table 4, the equilibrium calculation of two different mass ratios of methanol and hydrogen peroxide (50 %) are given together with the calculated adiabatic temperatures and the actual measured temperatures in the real gases. Since methanol is in excess, a decrease of the methanol ratio will result in increased temperature. A decreasing of the methanol content from 33 to 27 w % increases the temperature from 600 to 750 °C. This has consequences for the lower heating value (LHV) of the produced gas that sinks from 5.2 to 3.8 MJ/kg

4.4 Turbine unit

The design of the turbine is based on the basic requirements seen in table 6. Here, only the thermo-aerodynamic design of the turbine is considered. The turbine inlet fluid is assumed to be a gas mixture of H₂O, N₂, CO₂ and CO, see table 6. Here, it should be stressed that the design emphasize on finding a suitable small sized high-speed turbine (D_m=60-70 mm, single stage) generating sufficient shaft power.

A mean line design is performed for the turbine with the assumptions of perfect gas, $c_1=c_{2ax}=c_{3ax}$ and constant specific heat capacity ratio. Considering the requirements and from initial calculations it is decided to go for a partial admission one-stage turbine with a low reaction degree. Because of time restrictions a 2D profile is generated that has an acceptable aerodynamic performance at low velocity ratios and with certain leading edge roundness in order to cope with the flow angle deviations present in the partially admitted turbine.

Conservative calculations are performed iteratively to reach a converged solution without reaching transonic velocities in the rotor. General design parameters such as isentropic velocity ratio and pitch-to-chord ratio are selected and losses calculated in similarity with Traupel, [4]. Main turbine design parameters are shown in table 5 & 6, with flow geometry denomination according to table 5. The isentropic total to static turbine efficiency was calculated to 0.53 and the power output then estimated to 3.8 kW.

| Parameter | denomination | Initial design | Unit |
|-----------------------------|--|----------------|------|
| Pitch-to-chord ratio | s/C | 0.60 | - |
| Velocity ratio | $v_{ts}=U/(2*\Delta h_{ts,s})^{0.5}$ | 0.38 | - |
| Mean diameter | D _m | 0.066 | m |
| Blade height-to-chord ratio | H/C | 0.85 | - |
| Reaction degree | $R=c_x/(2*U)*(tan(-\beta_3)-tan(\beta_2))$ | 0.09 | - |
| Mean blade speed | U _m | 325 | m/s |
| Loading coefficient | $\Psi=c_p*\Delta T_{tt}/U^2$ | 1.82 | |
| Blade flow turning | γ | 125 | ° |
| Admission degree | ϵ | 16.1 | % |
| Inlet Mach number rotor | M _{w2} | 0.57 | - |

Table 5. Main turbine design parameters

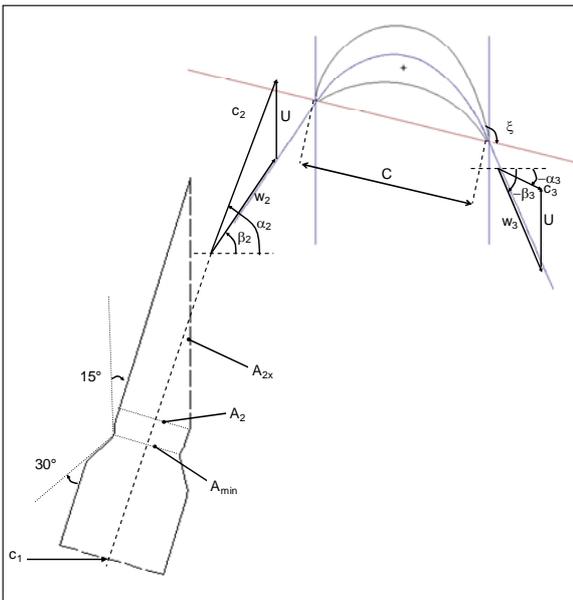


Figure 10. Turbine nozzle and blade lay-out

4.6 Power module

The power module was defined as the assembly of the turbine unit together with the load compressor. The compressor-turbine assembly had two preloaded angular contact ball-bearings of hybrid type. A separate lubrication system was incorporated. The bearings were lubricated with a synthetic oil.

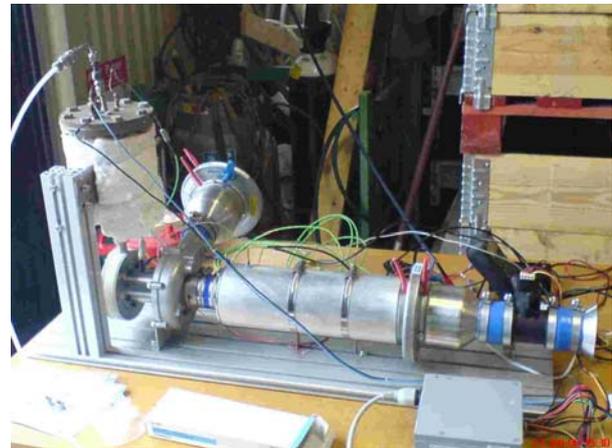
| Req. | |
|--------------------|-----------|
| Power (kW) | ~3-6 |
| Speed (rpm) | 80-100000 |
| Turbine eff. | >60% |
| Gas flow (kg/s) | 0,01-0,02 |
| Gas pressure (bar) | < 10 |
| Gas temp. (K) | ~1000 |
| Gas mixture | |
| H ₂ O | 50% |
| H ₂ | 30% |
| CO ₂ | 15% |
| CO | 5% |

Table 6. Power module design parameters

4.7 Test rig

The aim of the project was to demonstrate a turbine driven EPU using medium concentrated H₂O₂ solutions and methanol as additional fuel.

The test rig build up consisted of an integrated gas generator/power module/ air handling system. The power from the turbine was extracted by a load compressor. The airflow and pressure rise was measured at different powers. The test rig was equipped with adjustable air valves at both the inlet as well as the outlet of the load compressor. Pressure and temperature sensors were located in the power module. The gas generator had pressure tabs and thermocouples at the reactor inlet as well at the outlet. The airflow was measure with a hot wire measuring device. The reactor flows were controlled by two constant flow valves which kept the ratio between H₂O₂ and methanol constant



Picture 9. The test rig set up. Reactor and power module to the left and the air inlet and flow measuring device to the right.

4.8 Test results

The scope of the project was to demonstrate the feasibility of a turbine driven EPU using medium concentrated H₂O₂ solutions and methanol as additional fuel without optimizing the system. A test program was performed where the system performance was measured and analyzed. By throttling of the inlet and outlet air to the compressor different point of operation could be evaluated. Several tests were performed with both 50 % and 60 % hydrogen peroxide. The 50 % concentration showed the best performance characteristics. Below in the table are given the results of runs at two different loads, 75 and 88 %, using 50 % H₂O₂ solution with 27 w % methanol.

Performance of over 6 kW was achieved which was higher than predicted.

| | | |
|-------------------------|--------|--------|
| Load % | 75 | 88 |
| m_{gas} (kg/s) | 0.015 | 0.0175 |
| Tr1 (°C) | 416 | 450 |
| Tr2 (°C) | 773 | 776 |
| m_{air} (kg/s) | 0.064 | 0.088 |
| P1 (bar) | 1.014 | 1.00 |
| P2 (bar) | 1.39 | 1.66 |
| P2/P1 | 1.37 | 1.66 |
| ΔT_c (°C) | 40.4 | 66.8 |
| P_{mech} (W) | 2600 | 5900 |
| n (rpm) | 74,000 | 91,000 |

Table 7. Results from measurement at 75 % and 88 % loads.

The mechanical power (P_{mech}) was calculated from compression data according to the following relations:

$$P_{\text{mech}} = m C_p \Delta T_c$$

$$\Delta T_c = ((P_2/P_1)^{(\kappa-1)/\kappa} - 1) T_{c,1}/\eta_c$$

m = mass flow air (kg/s)

C_p = heat capacity air, 1000 (J/kg K)

ΔT_c = temperature increase over compressor (K)

P_1 = pressure before compressor (bar)

P_2 = pressure after compressor (bar)

$\kappa = (C_p / C_v)$, 1.4 for air

$T_{c,1}$ = temperature before compressor (K)

η_c = isentropic efficiency

P_{mech} = mechanical power (W)

n = rotor speed (rpm)

5 Conclusion

The studies of an environmental friendly turbine based EPU system here presented were very successful. The primary goals were successfully demonstrated specifically in the phases II and III. The studies showed that a small turbine based EPU in the 5-10 kW power range using a stored energy system based on medium concentrated hydrogen peroxide and methanol can be built with commercial technologies. A unique hydrogen peroxide reactor technology was also developed. However since the start of

these studies new improved battery technologies have been developed. These new high power Lithium-Ion batteries do also have high energy content up to 200 Wh/kg. In potential future developments of EPU-systems these new battery technologies must therefore be considered as a possible competitor to a turbine based system such as described in this paper.

Acknowledgments

The authors also like to thank the personnel at Catator AB in Lund and Svekon AB in Stockholm for the support and practical help during the demonstration phase III activities. Especially thanks to Mr Mikael Persson and Dr Fredrik Silversand at Catator AB and Mr Olle Eriksson at Svekon AB. The authors also like to recognize Mr Jens Fridh at KTH for the excellent turbine design for Demo 2.

Copyright Statement

The authors confirm that they, and/or their company or institution, hold copyright on all of the original material included in their paper. They also confirm they have obtained permission, from the copyright holder of any third party material included in their paper, to publish it as part of their paper. The authors grant full permission for the publication and distribution of their paper as part of the ICAS2008 proceedings or as individual off-prints from the proceedings.

References

- [1] 36th Power Sources Conference, proceedings of: p 398
- [2] Atlas Copco, PY 4419, 1999
- [3] Atlas Copco, "FMV-Demonstrationsmodell för hjälpkraftsgenerering, Slutrapport, 2002-06-20.
- [4] Traupel, W., 1977
"Thermische Turbomaschinen"
Vol. 1, 3rd Ed., ISBN 3-540-07939-4
- [5] Concentrated Hydrogen Peroxide. Summary of Research data on Safety limitations. Shell Chemical Corp. Industrial Chemicals Div., New York 1959. Report NP-7744; SC-59-44.
- [6] US5980843 Method and apparatus in catalytic reactions, Fredrik Ahlstrom Silversand, Catator AB, 1991-11-09