04

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Koncept

Experiments with nickel and hydrogen

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1. Summary

The energy situation in the world demands that all possible new energy forms should be investigated. The Swedish Defence Materiel Administration, FMV has therefore financed some very rudimentary experiments with nickel and hydrogen, trying to experimentally reproduce the excess heating power claimed by Andrea Rossi and Sergio Focardi and described e.g. in the Swedish technical newspaper Ny Teknik[1].

Four different reactor chambers were built, in which different forms of nickel were tested in contact with hydrogen at different pressures and temperatures. Some of the nickel samples also contained other metal as "catalysts" like lithium, potassium, and iron. In some of our samples the nickel was e.g. in micrometer large crystal grains, in other samples the nickel was in the form of nanometre grains embedded in zirconium oxide. Contacts were taken with many active researchers in the field, including Andrea Rossi, asking for guidance to find a functioning solution. Andrea Rossi could not reveal his catalyst for us but thought that we would get a small indicative response using just pure nickel and hydrogen. He also mentioned that a hydrogen pressure of at least 200 bar and a temperature of 500 °C was necessary in order to see any effect without the catalyst. Piantelli, who is another researcher in the field, has stated that "" No catalyst is necessary. The trick is in the preparation of the nickel".

Neither significant excess heat, nor any radiation indicating nuclear reactions, have however been detected in our experiments. We can though not completely exclude that a reaction, resulting in a very small power output, took place.

While searching for information over the Internet we stumbled over the aneutronic reactions. They are not on the main line for research about future nuclear power, but the field could possibly be explored at a reasonable price.

One such aneutronic reaction is e.g. lithium liquid bombarded by protons

$^{7}\mathrm{Li} + {}^{1}\mathrm{p} \rightarrow 2\,{}^{4}\mathrm{He} + 17.35\ \mathrm{MeV}$

Lord Rutherford's students Cockcroft and Walton verified experimentally such reactions in 1932 and the yield for each reaction could be 100 – 500 times more energy output than the energy input[2] invested in the bombarding particle. The problem using lithium in its solid state was though the low probability for a nuclear reaction to occur (low cross section). The same processes, then using liquid lithium, have however been claimed to produce a much higher reaction probability[3]. If it is large enough for practical nuclear energy purposes remains to be proven.

For a more common use of nuclear energy the aneutronic reactions have the advantage of not creating large amounts of radioactive waste. Some more thoughts about this are at the end of this report (Chapter 5). If other independent researchers cannot repeat the Focardi/Rossi

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[1] Mats Lewan, Cold fusion: 18 hours excludes burning *(of hydrogen)*, Ny Teknik 2011-02-23

[2] http://plato.stanford.edu/entries/equivME/

[3] Hidetsugu Ikegami, Toru Watanabe, Roland Pettersson, Kjell Fransson, Ultradense Nuclear Fusion in Metallic Lithium Liquid, Energimyndigheten, ER 2006:42. (also given as number 16)

experiments, we think that some resources could be diverted to further investigation on fusion in liquid lithium. Even if the probability of success is small, a positive result could have very large implications.

2. Short theory concerning nickel-hydrogen

Focardi et al claimed anomalous heat production already in 1994[4]. Focardi and Rossi made an attempt to physically explain of the phenomenon 2010[5]. According to this there are many possible nuclear reactions between nickel and hydrogen leading to excess heat.

$$Ni^{X} + p^{1} \rightarrow Cu^{X+1}$$

Except for the stable isotopes of copper (63 and 65) the copper will then decay back into nickel again according to:

$$Cu^{X+1} \rightarrow Ni^{X+1} + e^{+} + \nu$$

Subsequently the e^{+} particle would be annihilated by:

$$e^{+} + e^{-} \rightarrow \gamma + \gamma$$

This resulting gamma radiation should normally be easy to detect, as it is around 511 keV. According to an email conversation with Hano Essén[6] and Rossi, Rossi has received measured spectra of electron-positron annihilation at 511 keV.

When going through the different isotopes of nickel, it can be concluded that quite a lot of energy would be released per reaction [from Rossi Focardi[7]]. Of course the natural isotope concentration of nickel is important, so the reaction rate of all the isotopes must be taken into account.

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[4] S. Focardi, R Habel and F Piantelli, Anomalous Heat Production in Ni-H Systems, Il Nuovo Cimiento, Note Brevi, vol 107 A, N. 1, 1994

[5] S. Focardi, A. Rossi, A new energy source from nuclear fusion, Physics Department, Bologna University and INFN Bologna Section and Leonardo Cort (USA), 2010.

[6] Hanno Essén, KTH, personal communication

[7] S Focardi, A Rossi, A new energy source from nuclear fusion, Physics Department, Bologna University, 2010

Tab. 1 The energy per reaction from Rossi Focardi[5] in MeV

Nucleus	$Ni^A + p^1 \longrightarrow Cu^{A+1}$	$Cu^{A+1} \longrightarrow Ni^{A+1}$	$Ni^A \longrightarrow Ni^{A+1}$
Ni^{58}	3,41	4,8	8,21
Ni^{59}	4,48	6,13	10,61
Ni^{60}	4,80	2,24	7,04
Ni^{61}	5,86	3,95	9,81
Ni^{62}	6,12		6,12
Ni^{63}	7,2	1,68 (Ni) 0,68 (Zn)	8,22 + 2,14
Ni^{64}	7,45		7,45

To get a practical hint of how high the energy developed is, one can compare with the annual heating need of a typical Swedish house of 25 MWh/year. If we assume that each reacting nickel molecule gives 5 MeV totally, 25 MWh corresponds to about 55 g of Ni reacting annually with about 1 g of hydrogen.

There were experiments made already in 1996[8] that tried to explain the Forcardi measurements in another way.

The prerequisite for the reactions above is that the coulomb barrier can be overcome. The coulomb barrier would repel the positive nickel core from the positive proton in the hydrogen core and almost totally prevent them from reacting. Another way of saying this is that conventional nuclear physics would never allow a reaction between nickel and hydrogen at the temperature levels used. It has therefore been assumed that some unknown mechanism allows the reaction to take place. As we cannot explain the nature of the reaction we chose to try to experimentally verify it first. If we could achieve any significant reaction at all, we would then try to find the best theoretical explain later.

Rossis experiments as they are described by Ny Teknik[1] seems to be have been set up according to figure 1 below. The amount of water fed into the reactor and then evaporated per second was measured and was used to estimate the resulting power, knowing the heat of evaporation of water.

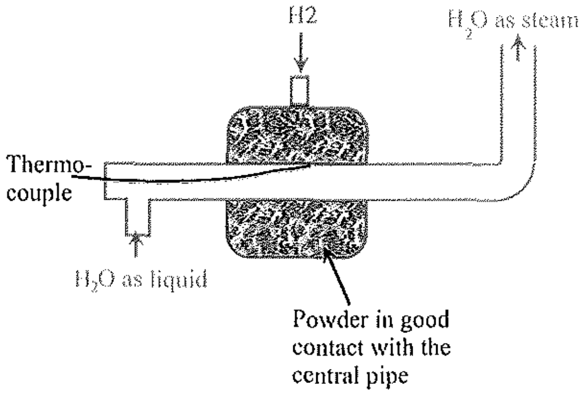

Fig. 1. Rossis measurements of power.

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[8] E. Cerron-Zeballos, I. Crotty, D. Hatzifotiadou, J. Lamas Valverde, M. C. S. Williams and A. Zichichi, Investigation of anomalous heat production in Ni-H systems, LAA project, CERN - Geneva Switzerland, 1996

3. Our experiments

3.1. General Method

When heating a sample inside a test tube, in room temperature and using an internal electric heater, the tube temperature will follow a certain curve. If a higher power is added to the sample the curve will rise faster and the balance temperature difference to the room air will rise.

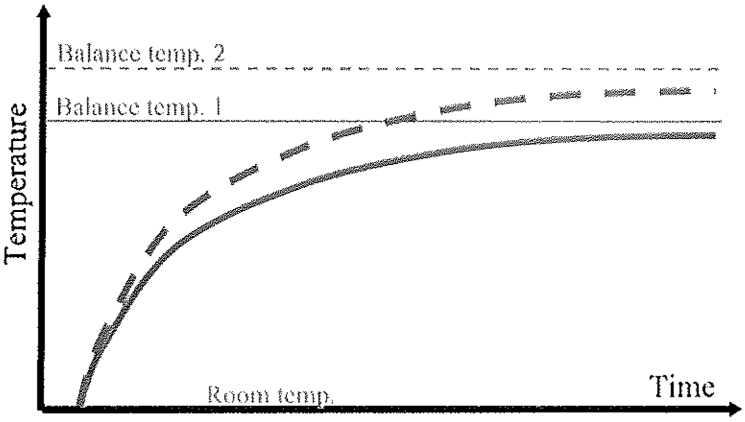

Fig. 2. The rise of temperature with a lower (continous) and higher (dotted) power used inside a test tube.

Another practical way that we used by us was to maintain the balance temperature constant and then measure the fluctuations in the electric power supply needed to keep that temperature. An exothermal reaction would then lead to that less current had to be supplied to maintain temperature (and pressure) in the constant test volume. One practical problem was that hydrogen when chemically absorbed in metals like nickel yields an absorption heat output and a simultaneous pressure reduction in the hydrogen. The amount of hydrogen that the nickel can absorb and hold is also affected by temperature. This chemical absorption heat is a however only a short time event. The expected heat from nuclear reactions was expected to contain much more energy and last longer.

One form of calibration was done with a nickel powder sample using inert argon-gas as a substitute for hydrogen and with a carefully measured electric power. When adding more electric power a higher balance temperature results and from that, the difference in temperature as a function of the power can be deduced. If the convection around the tube and radiation from the tube would be proportional to temperature the curve would be linear. That is however a somewhat too large simplification in this case. The reactor tube exterior was also insulated, which made the sensitivity for a power change much larger than for an uninsulated tube. In later experiments a detection limit of about ~1W excess heat was achieved. The first experiments were cruder and a the estimated detection limit was about 5W.

In addition to the temperature measurements we used a GM-detector to measure radiation. This gamma detector was calibrated with a Ba 133 radioactive sample emitting at 80 and 356 keV gamma radiation as the highest peaks.

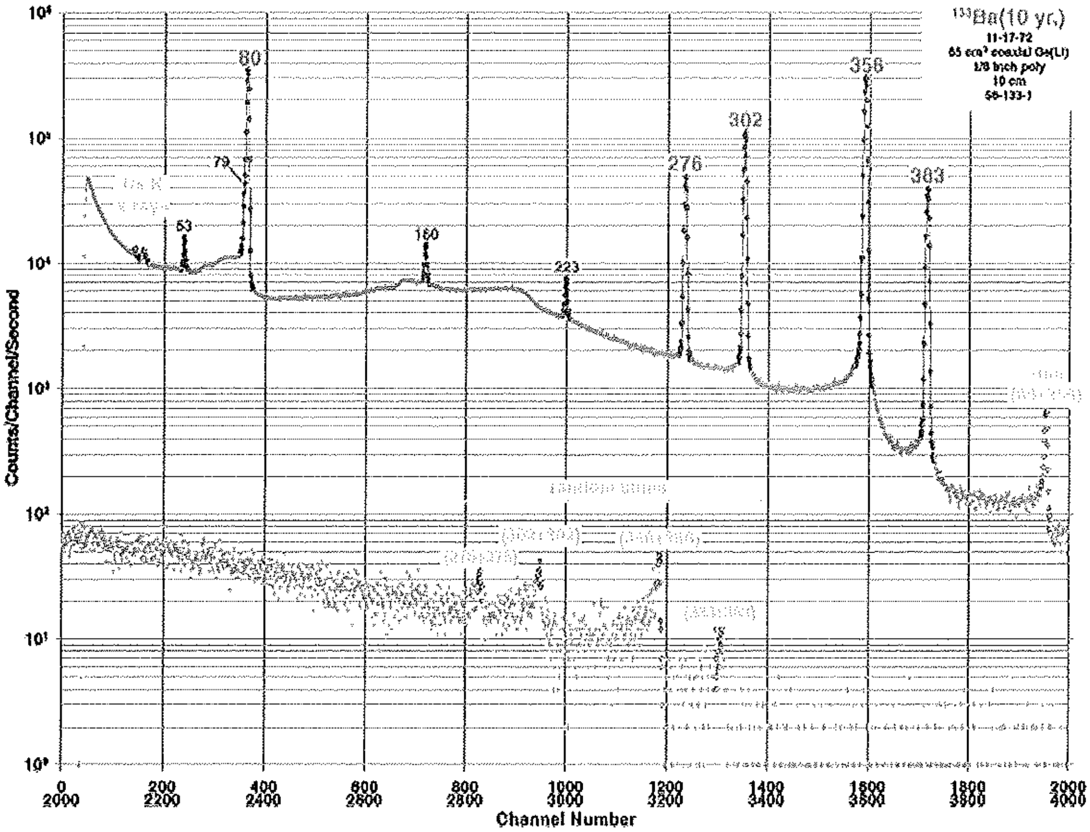

Fig. 3. Spectrum from Ba 133

3.2. Test equipment

3.2.1. Reactor vessels used

The experiments started with a rather large reactor, which soon was decommissioned in favour for a small, but more high-pressure tolerant reactor. This was done because Rossi claimed that a higher pressure in the range of 200 bars, should be used to achieve higher power without adding any catalyser.

Fig. 4. A, B, C. Different reactor vessels that were used

The first vessel in Fig 4A was made for about 35 bar, the reactor in fig 4B for about 300 bars and the reactor vessel in fig 4C are shown in cross section below in figure 4. This was the last (and best) vessel we used. This vessel could also only safely withstand 350 bars at 700 °C. The high-pressure 300 bars model was made in two improved versions, reactor 2 and 3.

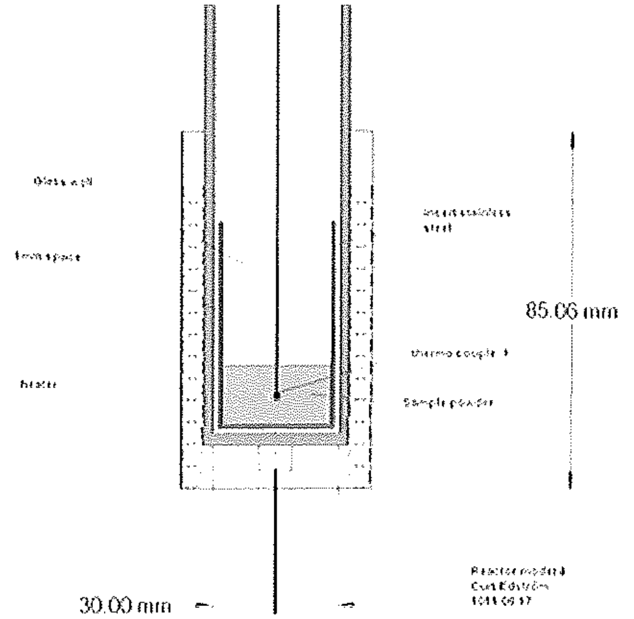

Fig. 5. Reactor vessel 4 – layout principle

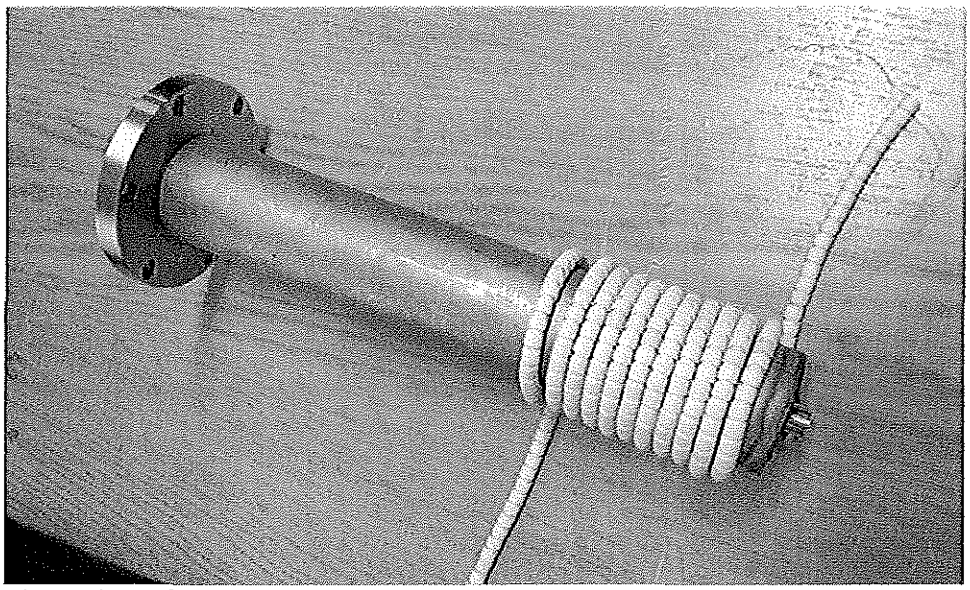

Fig. 6. Dimension of the outer tubing, OD 35 ID 30mm.

The heating wire was made of Al_2O_3 ceramic insulated Kanthal wire. The maximum power was 300W and it was wrapped around the bottom of the tube. The heating wire was insulated outside using glass and stone wool. As can be seen from fig. 5 there was an extra container inside reactor 4 holding the nickel powder that was going to be tested.

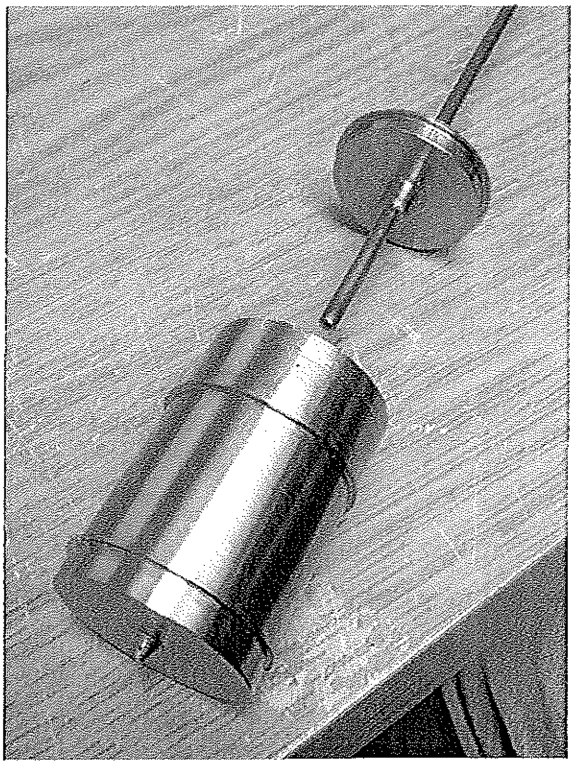

Fig. 7.. The container in the bottom of the tube.

The spacing was 1 mm around and 2.5 mm in the bottom of the container. The gas or vacuum in that space influenced the heat flow to the container slightly, which later became an, however minute, evaluation problem. The main advantage is that it caused the container to be slightly thermally insulated, and if any reaction would occur, the temperature rice in the chamber would be rapidly increased making it easier to detect. The inside diameter of this inner container was 26 mm. It was 40 mm high and the wall thickness was 1 mm. The chosen material was stainless steel. Two holes (8 mm) were drilled in the lid so that H_2 gas could enter the container (not yet drilled in this fig 7 lid picture). The thermocouple was held in position by the lid. Glass wool was placed inside the container mainly to keep the powder in place. This device was very easy to operate and very stable.

3.2.2. Heating and controlling power

The power was kept constant using a PID-regulator – it is shown in the figure below. For an experiment of this type it is of outmost importance that the electric power is known and can be controlled accurately.

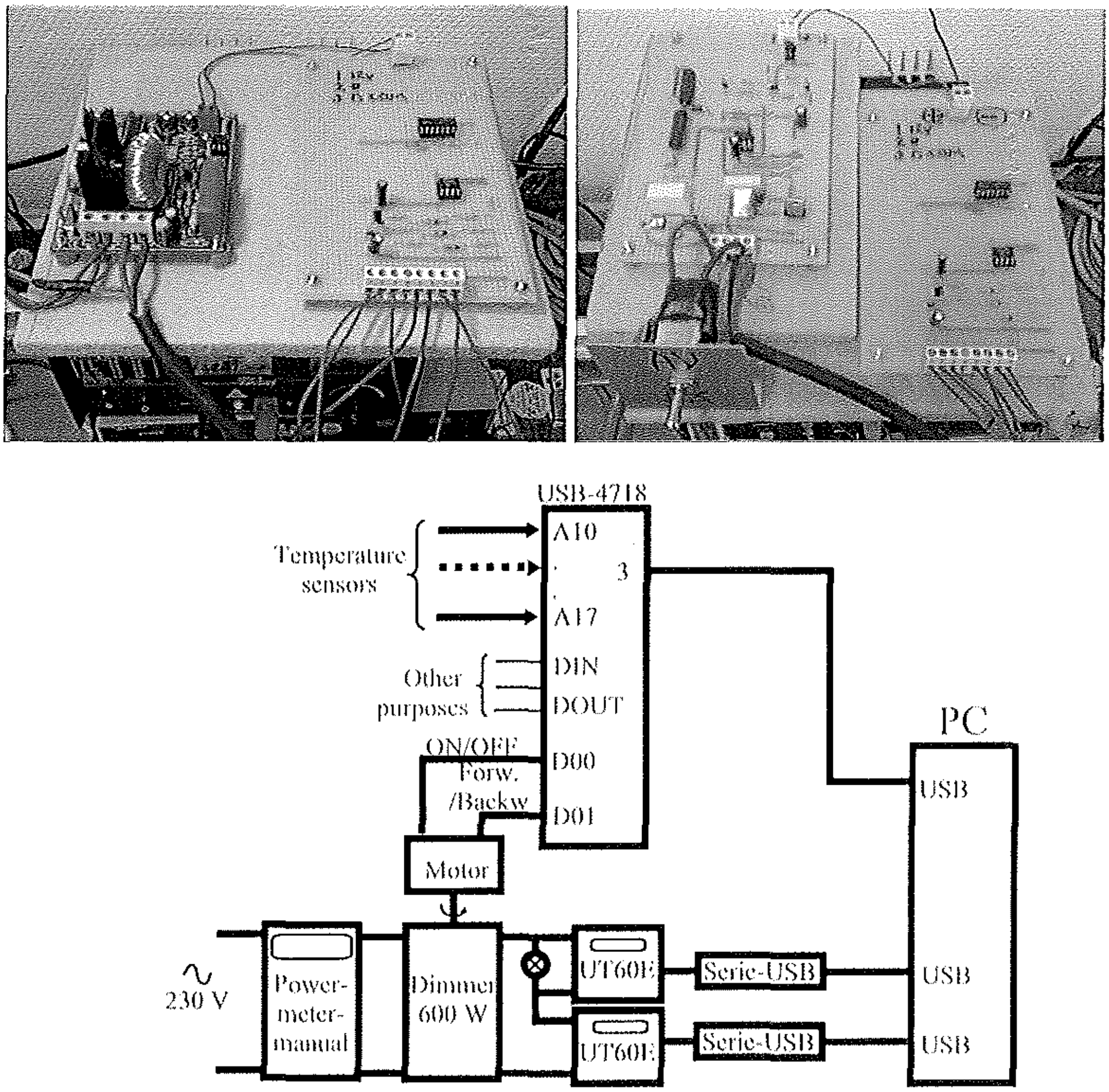

Fig. 8. The PID-regulator for power – original and improved version.

The control of the dimmer was not done with at "physical motor". It was done purely electronically using optically insulated transducers. Specially written software, Lofflab, was developed so that sampling of data could be done.

3.2.3. *Evacuating and filling gases*

Before each experiment the reactor vessels were evacuated after which either argon (as dummy gas) or hydrogen was supplied. The first scrapped version, Reactor 1, looked like the system in figure 10, after having fitted all necessary valves .

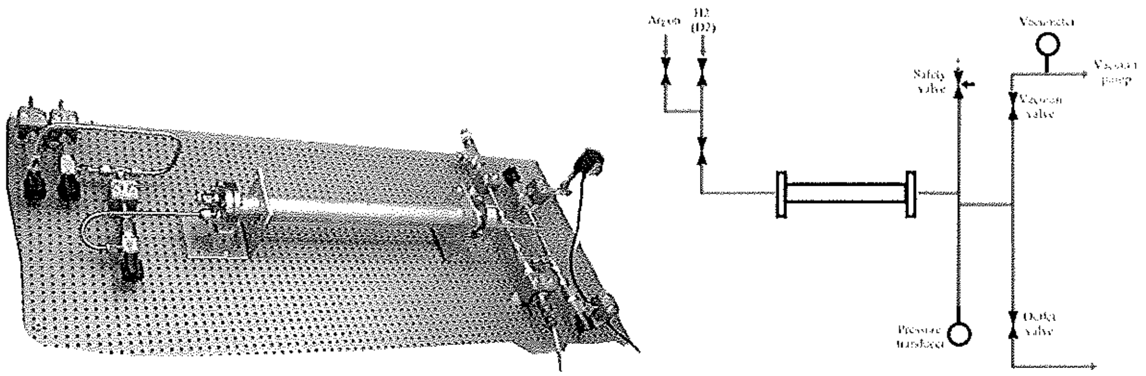

Fig. 9. Supply of gas, pumping vacuum and safety valves for reactor 1.

One difficulty that consumed many hours was to get the rig gas tight, especially for hydrogen. The best way was to look for how fast a high hydrogen pressure decreased while maintaining the same temperature.

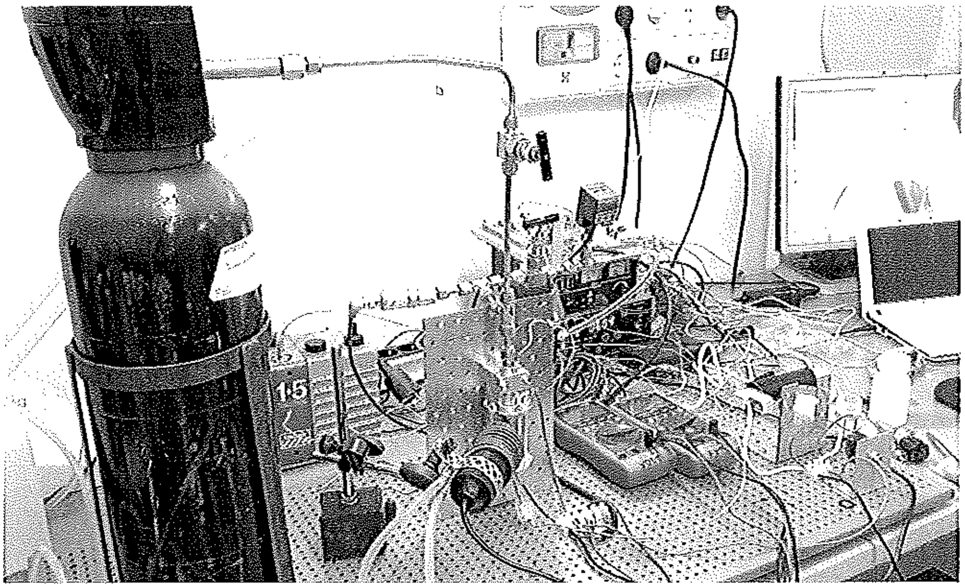

Fig. 10. This was the setup with reactor 3, during the 200 bar tests.

The only difference with this setup and reactor 4, was that a reduction valve was fitted resulting in a pressure limit of 25 bar for the low pressure vessels. All other features were kept the same.

3.2.4. *Measuring γ-radiation*

Rossi warned for radiation dangers. The radiation was said to be "soft" between 30 keV and 150 keV. A rather simple GM-tube was therefore bought and calibrated using a 1 micro curie Ba 133 (Barium) source. The Ba 133 source gave a significant output, even when it was placed behind the reactor so the gamma photons had to pass through several mm of steel indicating that we should be able to detect radiation in the same level as the reference. The photons emitted from Ba 133 have a broad spectrum of energies and was from that point of view suitable for calibration. The Ba 133 energies emitted is between 3 and 383 keV[9] (and fig 3). During the experiments the detector was placed in proximity to the reactor wall and therefore had to be protected from thermal radiation by a thin water-cooled brass plate.

Fig. 11. The γ-detector shielded from thermal radiation by water-cooling.

No γ-radiation was ever detected, more than background levels, from any of the tests.

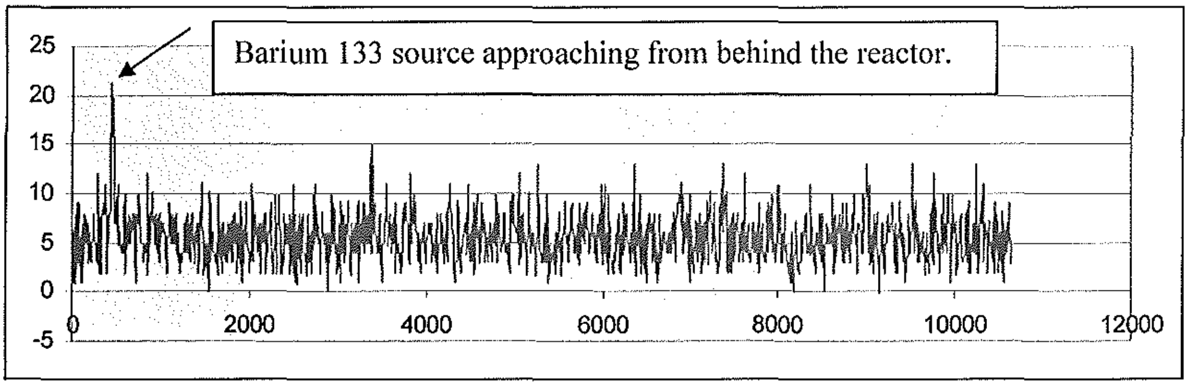

Fig. 12. No γ radiation above background noise level was detected at any time in any experiment.

The Gamma emission was continuously sampled in 10 seconds intervals and analysed.

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[9] http://ie.lbl.gov/toi/nuclide.asp?iZA=560133

3.3. *Samples used*

3.3.1. Examples of different metal (nickel) powders tested

To achieve a maximum contact surface between the metal and the hydrogen the samples used were in some form of powders. The grain size varied between a micro- and nanometres. Large grains or plane surfaces such as pipe-walls were considered as less suitable for testing this type of reaction as the surface to volume ratio is low.

Tab. 2 Some examples of the powders used or just bought

Type	Main metals % by weight	Grain size	From	Remark
1	Ni	100 nm	Nano Dynamics	Unknown quality
2	Ni		Israel	Carbonyl Nickel
3	Ni 90%, Fe 9%, Li<0,5%	100 nm	Own make	Noval
4a	C 4.18%, O 23%, Ni 5.4%, Si 0,21%, Zr 65%, Pd 0.86%	3 µm	Ahern EDS-analyze 1	Undamaged particle surface (see also Appendix 1)
4b	C 14%, O 17%, Ni 18,5%, Si 1.5% Zr 47%, Pd 1,6%	3 µm	Ahern EDS-analyze 2	Average value from many grains
4c	C 10% o 17,5 Ni 20%, Si 0.9%, Zr 46% Pd, 2,8%	3 µm	Ahern EDS-analyze 3	Very fractured piece

After our first attempts to find pure Ni powders, resulting in a reaction, we resorted to ask people, who over the Internet, that said that they had powders that had resulted in some form of reaction. Brian Aherne[10] was one such person (sample 4 a-c). The samples from Aherne were analyzed using EDS-analysis. On some specific spots the content of Pd vas very high. It is clear though that the Pd was very unevenly distributed. Only one of these samples from Ahern was finally tested in the reactor, experiment 25 and that sample had been previously used.

When using high temperatures, the powders sintered together, forming, a still hydrogen-permeable, lump. It was always attempted to prevent NiO from forming on the grains. One way of preventing that was to heat the samples to high temperatures – over 360°C in a reducing hydrogen atmosphere - and cycle it several times by vacuum pumping.

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[10] Brian Aherne, Vibronic Energy Technologies Corp, http://www.scribd.com/mjstrand1/d/39076066-Vibronic-Energy-Technologies, and personal communication

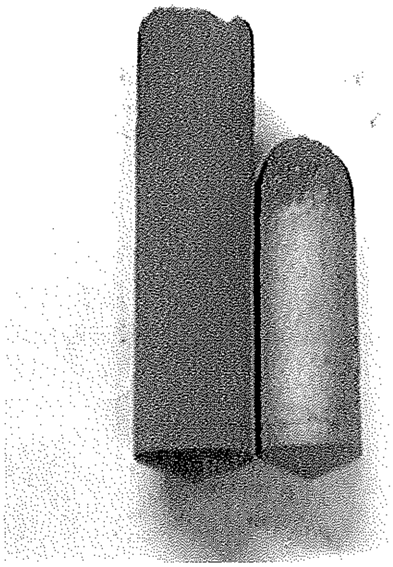

Fig. 13. Powders where the grains have sintered together. The sintering resulted in very solid metallic appearing lumps however still porous.

3.4. Used pressures and temperatures

The hydrogen pressures ranged between a few bars to 200 bars. The temperatures varied between room temperature to over 600 °C.

As no significantly powerful reactions were found during the experiments, only a few tests, with comments of how the experiments were conducted, will be shown. The raw data are available on demand.

3.4.1. 2011-04-21 Curt Edström Experiment 1

Pressure 33-29 bars using hydrogen.
Ni 100 nm grains from Nanodynamics - 2.6 gram.

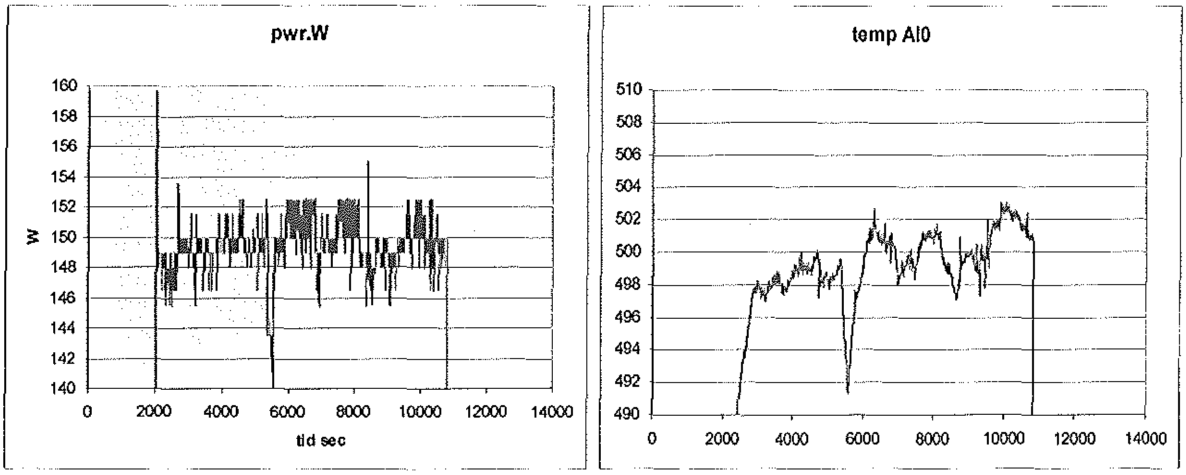

Fig. 14. Supplied power and resulting temperature. This was an early test with crude control of the power. The later experiments performed with better power accuracy. This experiments shows a very stable temperature, fluctuating only about 4°C indicating no reaction.

3.4.2. 2011-07-25 Experiment 25, reactor 4.

The pressure had first been varied between vacuum and 13.6 bar after hydrogen insertion. Aherns ZrCuNi mixture (see table 2, mixture 4 a) was used. The sample had been baked at 500°C over night in vacuum at 62 W power. This time the power was kept very controlled and constant. The temperature in vacuum had remained very stable at 479 °C the whole night (+/- 1deg.).

Hydrogen was then introduced at 13.6 bar, after 64 000 sec. The pressure lowered by 0.5 bars during less than 3 hours (a rather small pressure drop). The temperature first increased to 505°C then slowly dropped to stable 498.8°C. The rise between 505 °C and 498,8 can be attributed to absorption of hydrogen in the powder. The rise between 479 and 498,8 is most likely due to better heat conduction between the heated pressure vessel and the powder container inside fig 7.

When vacuum was restored again the temperature returned and stabilized around 480°C. As we have been told by e.g. Rossi, the powder had to be cycled several times to get "active" and as the power from a possible reaction would also come in "bursts". We have therefore taken this experiment as an example of what happens when using "inert virgin" Ni-powder. A further discussion of this sample-powder will be done below.

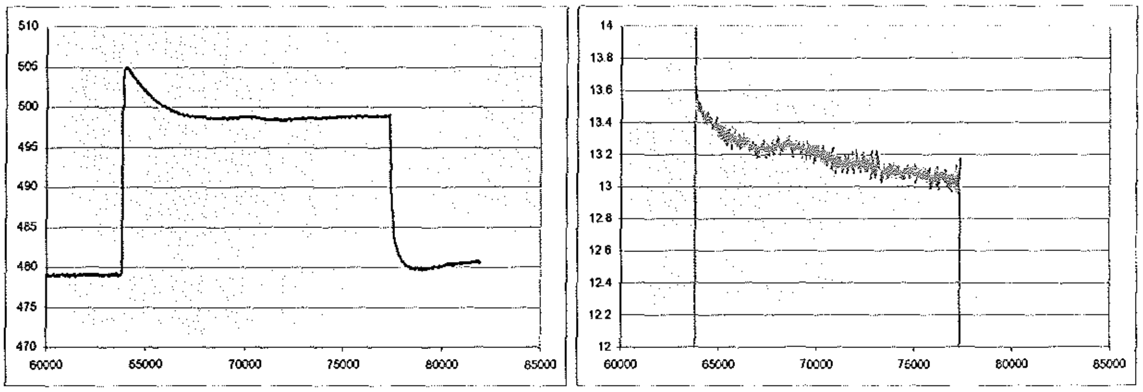

Fig. 15. Fig 13 Temperature °C curve at measuring point A0 (left) and the pressure in bars (right), after insertion of hydrogen (and then re-evacuated to vacuum).

4. Discussion of results

4.1. Detection limits of measurements

Let us for example take test number 23, which was first tested as a "dummy". The powder had never earlier been exposed to hydrogen. As earlier mentioned - according to what we have gathered from e.g. Rossi, the powder must first be cycled in hydrogen several times to become active. When some nuclear reaction, occurs it was also said to come in "bursts" (the length of these "bursts" were however largely unknown to us). We therefore assumed that experiment 23 was an experiment representing zero output of the nuclear reaction energy sought for. First some more data about the experiment:

Run 23, 2011-07-18, first test with reactor 4.
70 W continuous input power.

Pressure 2.05 bar cold start.
Mass of powder 8.3 g

Measured channels
A0 internal probe, A1 air temperature, A2 probe outside at bottom, A3 outside at top of heater
A4 GM tube, A5 Top of flange (near safety valve)

Observations:

It takes about 2 hours before it gets stable. The observed pressure decrease is from absorption only. There is also a pressure rise at 6000 s - this is due to a pressure check. The volume of the reactor was 137 cm³ (195 mm x 30 mm diameter), The volume of the tubing is around 5 cm³ yielding a. total volume of 142 cm³ (minus the volume of the test-powder).

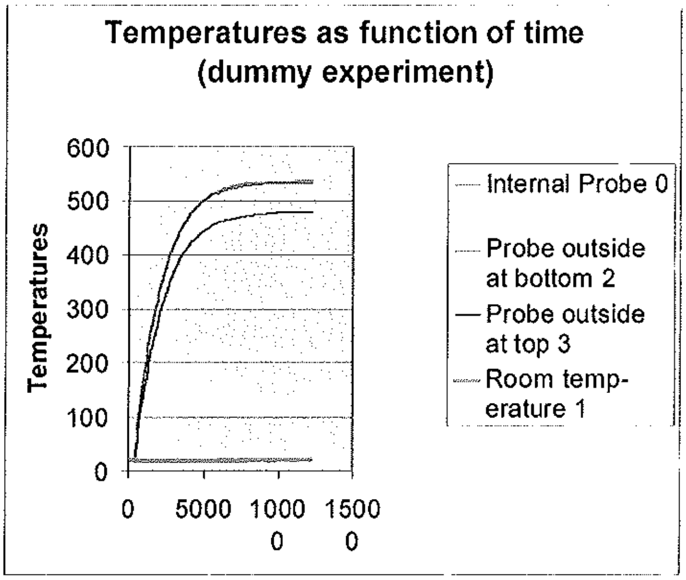

Fig. 16. Test 23 with dummy gas (argon)

The question that arises is: If extra power would be added due to a nuclear reaction, would that be detected by us as a temperature rise? If we enlarge the steady state part of the figure above we can se that a temperature difference to the surrounding of 538°C to 22°C corresponds to a power of 70 W. That means that a step in power of 1 W would roughly give a step in temperature of 7 K.

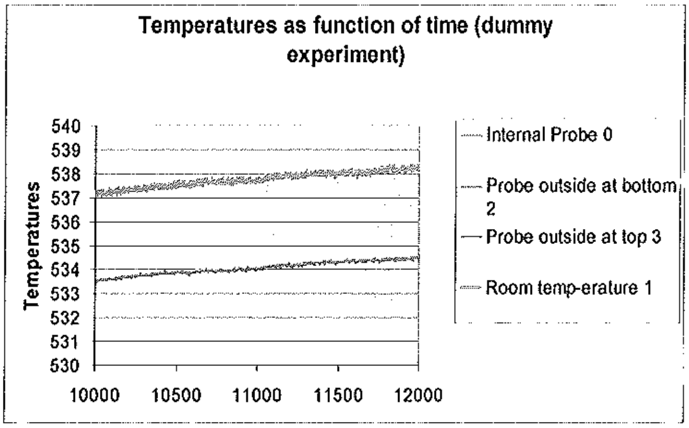

Fig. 17. Test 23 above magnified

It is possible to see a small ripple in the temperature reading of the innermost internal probe 0. The amplitude peak to bottom of that ripple is in the order of 0.2°C. It cannot be completely ruled out that this ripple arises from any nuclear reaction – however the power is then in the order 0.2 / 7 W or 0.03 W.

From an inertial point of view, on a more macroscopic level, only steps in power that are long enough, meaning that they contain enough energy, would be detected. An upper boundary for that sensitivity can be calculated using the mass of the **whole probe** times its specific thermal capacity, which is about 300 J/K. A one degree increase would then require 300 J of energy. If it is not an instantaneous step however, but rather a slow triangular power ramp rising and affecting the whole mass (300 J/K) it would be very hard to detect using our methodology.

A lower boundary would be just looking at **the powder** itself = 8.3 g multiplied by say 666 J/kg K (the powder is very inhomogeneous, see appendix 1) yielding ~5.5 J/K. If we then assume that 1 K would be a detectable temperature rise that would correspond to an energy pulse of only 5.5 J.

Later, in run 25, the same sample had been exposed to cycling in hydrogen several times, and should then be somewhat more active.

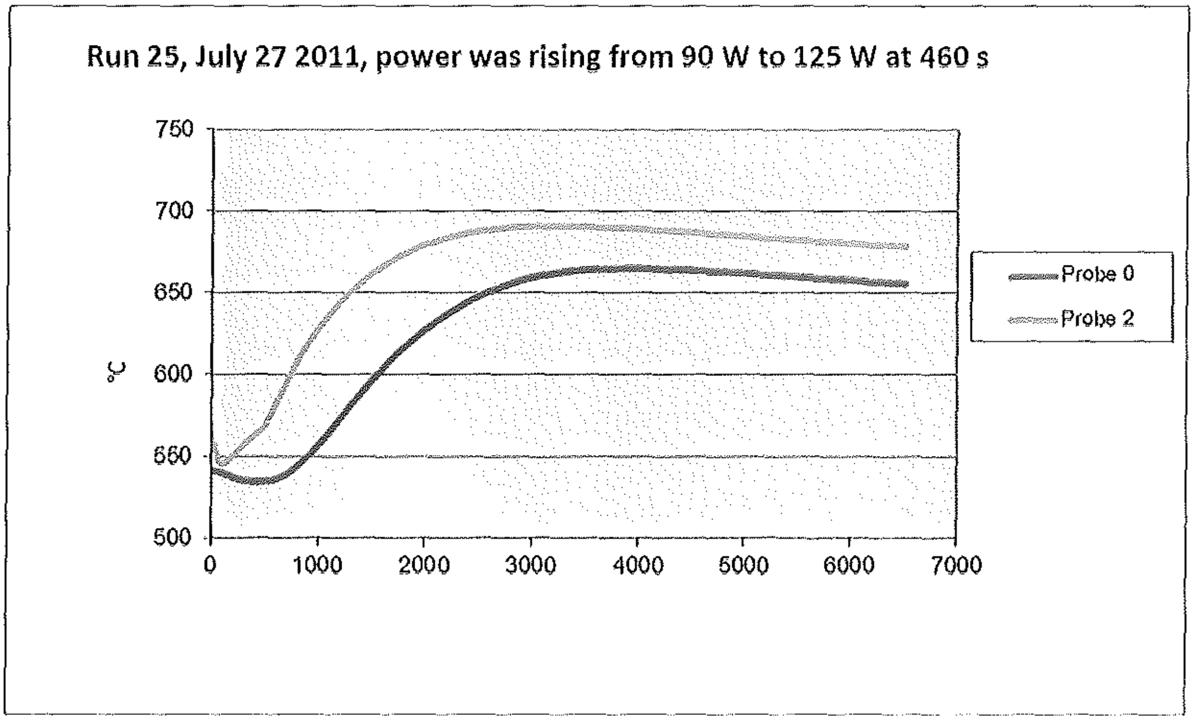

Fig. 18. High power experiment (125 W)

As can be seen from these curves even at 125 W the sample (probe 0) rises to a temperature of 666 °C which means that 1 W at this temperature level gives a temperature rise in the powder of 5 K (= 125 / (666 - 22)). The reason that 1 W is only giving a rise in temperature with 5 K instead of 7 K in this case is of course the higher temperature. Hot bodies radiate a large part of their energy to the surrounding proportionally to T^4 whereas convection follows just T. The data obtained here indicates that the radiation is the by far the dominating way of heat transfer from the sample. The reason for the slow temperature dropping at the end is likely that the insulation around the test tube actually started to melt at these high temperatures.

The same sample was first tested in vacuum and then with hydrogen gas. Heating started now using 60 W (instead of 70 W or 125 W). When the temperature had stabilized in vacuum at 477 °C, 10 bar of hydrogen vas loaded. Thereafter the temperature was stabilized for a couple of hours. Due to large amount of data the curves have been divided into three sets - set 1, 2 and 3.

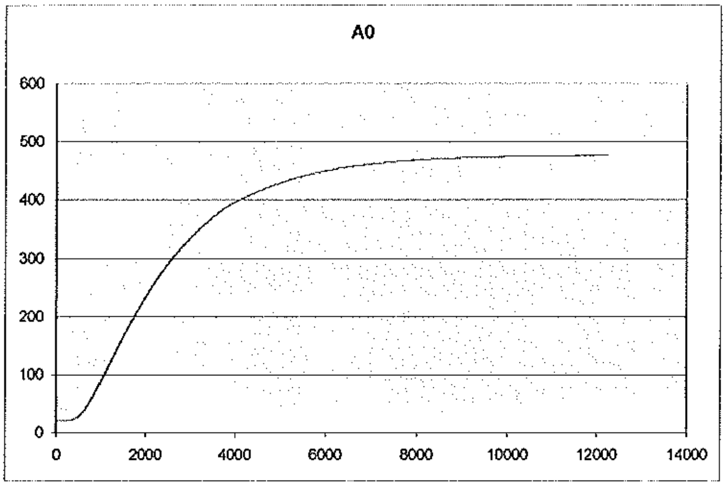

Fig. 19. Test 23 temperature in powder sample continued in vacuum – A0 is the in the sample (set 1)

At 2600 sec in set 2, H2 was injected with a pressure of 10 bars. The temperature in the sample then rapidly rose to 497 °C and thereafter slowly lowered again to 490 where it stabilized. From 7000-10000 s in set 2, the sample temperature is constant. This indicates no more H_2-absorption in the sample explaining the stability. When the gas pressure, after that, was lowered to vacuum, the temperature immediately dropped back to the original temperature in vacuum of ~477 °C.

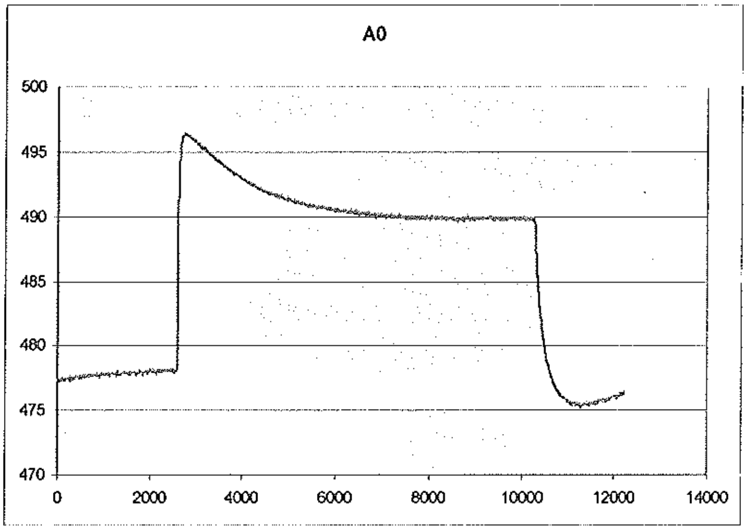

Fig. 20. Test 23 continued (set 2) introduction of H_2

The vacuum curve in figure 20 can be explained by first an increase in heat conduction between the heater and the powder at 2600 s - then a chemically developed energy between 2600 s and 8000 s as hydrogen is absorbed by the sample powder. Finally there is a plateau at about 490 °C from 8000 s to 10000 s and then a drop back to 477 °C as the hydrogen is removed again diminishing the thermal contact between thermocouple A0 and the heater.

There are many variables involved for determining the heat released when hydrogen is chemically absorbed in a metal. 14.6 MJ of heat / kg hydrogen absorbed, is given in ref[11]. Baranowski et al[12] on the other hand gives 17.6 MJ/kg for Ni. (In ref [13] however only 0.588 MJ/kg is given for absorption in pure Ni and 1.454 MJ/kg if palladium is added! Most probably a misunderstanding from my side)

The pressure in the 142 cm³ hydrogen compartment fell from 10.7 bars to 9.5 bars during the test see fig 21. According to the normal gas laws:

$$p \cdot V = \frac{m}{M} \cdot R \cdot T \tag{1}$$

$$\Delta p \cdot V = \frac{\Delta m}{M} \cdot R \cdot T$$

$$\Delta p = (10{,}7 - 9.5) \cdot 10^5 = 1.2 \cdot 10^5 Pa$$

$$V = 142 \cdot 10^{-6} m^3$$

$$M = 2\ kg / kmol$$

$$R = 8314\ J / kmol \cdot K$$

$$T \approx 273 + 500\ K$$

$$\Delta m = \frac{1.2 \cdot 10^5 \cdot 142 \cdot 10^{-6} \cdot 2}{8314 \cdot 773} = 5.3 \cdot 10^{-6} \left[\frac{kg}{m \cdot s^2} \cdot \frac{m^3}{} \cdot \frac{kg}{kmol} \cdot \frac{s^3 \cdot kmol \cdot K}{kg \cdot m^2} \cdot \frac{1}{K} \right] = [kg]$$

Assuming that ref 11 is right, the heat developed from that is then $14.6 \cdot 10^6 \cdot 5.3 \cdot 10^{-6} = 77$ J. This energy would be released directly in the sample powder. The mass of the sample was 8,3 g and the heat capacity of the powder is estimated to around 666 J/kg K see appendix 1. If this energy would come in a step while introducing the hydrogen and mainly take place in the powder sample the temperature increase would be around 14 K. The excess power in W during the whole period is however much too small to be detected.

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[11] L. Kit Heung, Using Metal Hydride to Store Hydrogen, Savannah River Technology Center, WSRC-MS-2003-00172, http://sti.srs.gov/fulltext/ms2003172/ms2003172.pdf

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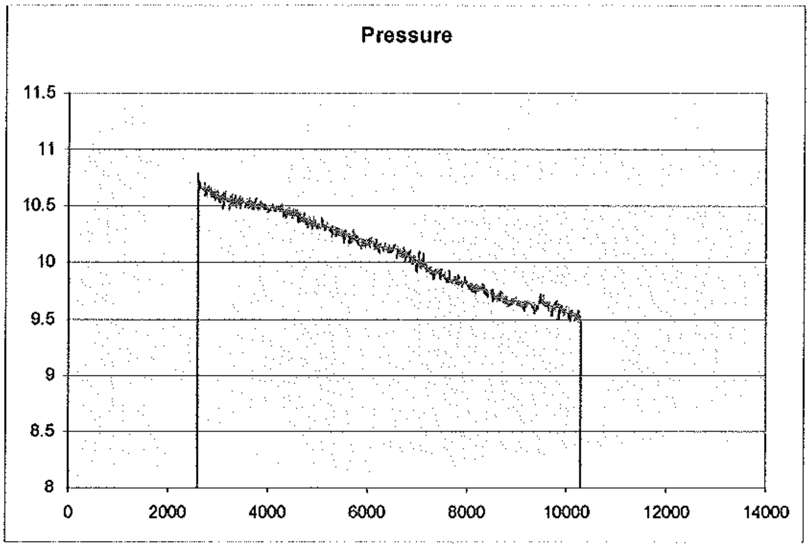

Fig. 21. The pressure during the hydrogen filled period

4.2. *Tests and procedures that could be performed.*

Brian Ahern has sent another powder samples containing ZrNiPd, which was unused and fresh. He ment, that this powder would be a good candidate for repeating a test under identical conditions as under his own tests. In view of the overall experiences with the earlier experiments however, we think there is a very low probability of success.

One problem that occurred with reactor 4 was that at an elevated temperature around 700°C the surrounding fiber-insulation partially melted, resulting in a different thermal response, thereby hampering the precision to detect excess heat. It the forthcoming experiment, this could be solved by insulating the reactor with "Vermikulit" that can withstand temperatures up to 1000 °C. The reactor would then be submerged in a container of this powder as insulator.

5. Suggestions for the future

There are many ideas about producing nuclear power. Many of them are very costly and complex like the ITER[14] and NIF[15] programs. Other are smaller and have a lower budget like the Crossfire fusion[16]. For nuclear energy to be commonly accepted (again?) some demands are desirable e.g.:

- No radioactive waste
- No risk for "explosions"
- No risk for proliferation of bomb material
- No risky mining for exotic materials

One group of nuclear reactions that seem to comply with these demands are the aneutronic reactions[17]. They do not emit neutrons and therefore do not result in radioactive waste. When driven by an accelerator they cannot "explode" and the materials needed exist abundantly. Two simple aneutronic reactions are e.g. (P is a proton, Li is Lithium and B is Boron):

$$P + {}^{11}B \rightarrow 3\ {}^{4}He + 8.7\ MeV$$
$$P + {}^{7}Li \rightarrow 2\ {}^{4}He + 17.2\ MeV$$

These reactions means that merging a proton with of Boron or Lithium converts them into 3 or 2 helium cores while also releasing a lot of energy. The reactions have been investigated as long as nuclear power has been an option, but no one has so far clearly demonstrated a practical technical solution giving off more energy than the whole process consumes. Cockcroft and Walton got a Nobel Prize for discovering these reactions and investigating them in 1951. Energy is required to merge a proton with boron or lithium as above, to overcome the Coulomb barrier.

The most common method anticipated to practically overcome this barrier in fusion is to heat the components in a high temperature plasma. The cores will then merge, crossing the Coulomb barrier, by shear temperature velocities of the cores. Billions of degrees are needed to overcome the Coulomb barrier and the plasma has then to be kept in place by e.g. magnetic fields. Cockcroft and Walton however, used an (today simple) accelerator and still achieved fusion as it is much easier to achieve a beam with the high speed ions needed, compared to a plasma.

The heat energy output from such a reaction could be typically 15 - 30 times the electric energy invested in the accelerated beam energy input. That is theoretically enough to get a net energy output after converting heat into electricity and feeding the accelerator. The probability for a fusion reaction is however very low when bombarding e.g. metallic lithium target with protons, deuterons or other Li^+ ions. It is typically less than one in a billion collisions that result in a nuclear reaction. The low reaction probability is among other reasons due to that the bombarding particles are "slowed down" while emitting radiation

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[14] ITER http://www.iter.org/

[15] NIF https://lasers.llnl.gov/

[16] http://www.crossfirefusion.com/nuclear-fusion-reactor/crossfire-fusion-reactor.html

[17] http://en.wikipedia.org/wiki/Aneutronic_fusion

"Bermsstrahlung", so that they very seldom hit the target with energy enough to induce a nuclear reaction.

5.1. *Liquid targets - chemo-nuclear fusion?*

In an interesting report from the Swedish Energy Authority (Ikegami[18] et al) it is stated that theoretical calculations show that there is a huge difference if a lithium target is in its liquid state as opposed to in its solid state. The probability for a nuclear reaction could thus be raised between 10^{15} and 10^{48} for a fusion reaction when the lithium target is in its liquid state as opposed to its solid state. The reason for this is that the lithium and the bombarding nucleus are held close to each other inside the electronic K-shell for much longer times, which enhances the tunnelling probability (chance for reaction). Practical experiments also supported the theory and significant enhancements were measured using a liquid target instead of a solid target.

Other experiments performed by T Minari et al in Kobe[19] in Japan, have however not verified the Ikegami theory[16]. Though an enhancement in reaction rate was observed in liquid lithium – it was much smaller than predicted in[16]. These experiments seem to have been performed at higher temperatures - 520 K and 570 K whereas the melting point of lithium is 454 K. That would, according to theory, yield a lower enhancement factor according to the theory shown[16] as the melting point seems to be the optimal temperature.

It would be interesting to try to again verify the Ikegami[16] predictions. If possible, a geometry and technique should be chosen, that would alleviate or avoid the build-up of unwanted by-products on the lithium surface. Corrosion in materials surrounding the target should also be somehow avoided. Uppsala university e.g. Roland Pettersson, has got large experience in this field.

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[18], Hidetsugu Ikegami, Toru Watanabe, Roland Pettersson, Kjell Fransson, ULTRADENSE NUCLEAR FUSION IN METALLIC LITHIUM LIQUID, © Statens energimyndighet, ER 2006:42, ISSN 1403-1892

[19] T. Minari, R. Nishio, A. Taniike, Y. Furuyama and A. Kitamura, Experiments on Condensed Matter Nuclear Events in Kobe University, Eleventh International Conference on Condensed Matter Nuclear Science. 2004. Marseille, France, Division of Environmental Energy Science, Graduate School of Science and Technology, Kobe University, Japan

6. Appendices

Heat Capacity, Cp, for Zirconium Oxide[20] Nickel Carbon, Silicon and Palladium[21] as a function of temperature

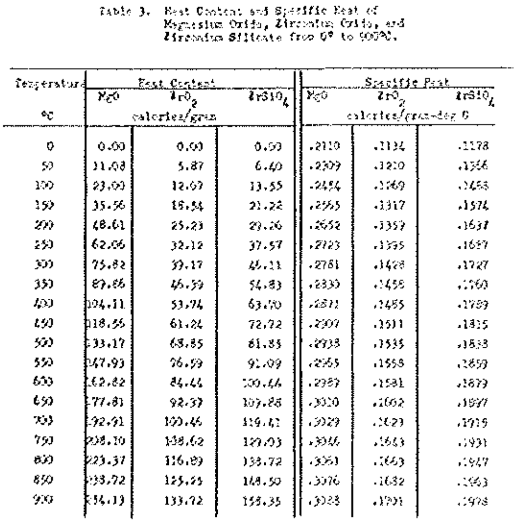
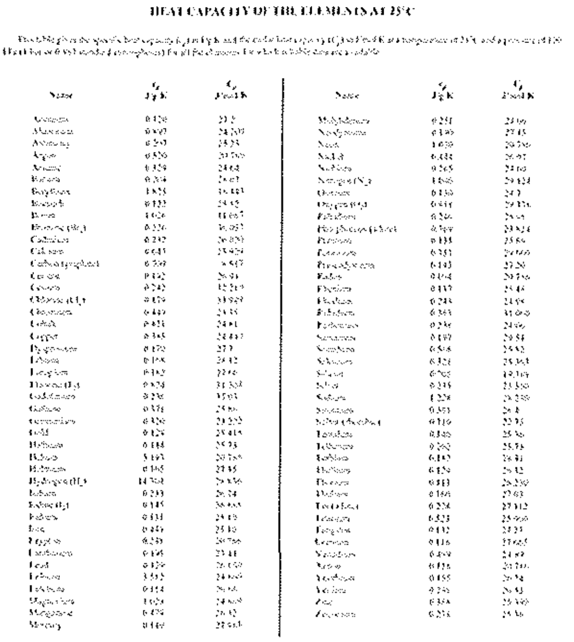


Table 3. Heat Content and Specific Heat of Magnesium Oxide, Zirconium Oxide, and Zirconium Silicate from 0° to 900°C.

Temperature	Heat Content			Specific Heat		
°C	MgO	ZrO_2 calories/gram	$ZrSiO_4$	MgO	ZrO_2 calories/gram-deg C	$ZrSiO_4$
0	0.00	0.00	0.00	.2110	.1134	.1178
50	11.08	5.87	6.40	.2309	.1210	.1356
100	23.00	12.07	13.55	.2454	.1269	.1455
150	35.56	18.54	21.22	.2565	.1317	.1574
200	48.61	25.23	29.26	.2652	.1357	.1637
250	62.06	32.12	37.57	.2723	.1395	.1687
300	75.82	39.17	46.11	.2781	.1428	.1727
350	89.86	46.39	54.83	.2830	.1458	.1760
400	104.11	53.74	63.70	.2871	.1485	.1789
450	118.55	61.24	72.72	.2907	.1511	.1815
500	133.17	68.85	81.85	.2938	.1535	.1838
550	147.93	76.59	91.09	.2965	.1558	.1859
600	162.82	84.44	100.44	.2989	.1581	.1879
650	177.81	92.37	109.88	.3010	.1602	.1897
700	192.91	100.46	119.42	.3029	.1623	.1915
750	208.10	108.62	129.03	.3046	.1643	.1931
800	223.37	116.89	138.72	.3061	.1663	.1947
850	238.72	125.25	148.50	.3076	.1682	.1963
900	254.13	133.72	158.35	.3088	.1701	.1978



HEAT CAPACITY OF THE ELEMENTS AT 25°C

For metals (and some other substances) he heat capacity values are following the Einstein-Debye phonon model[22] **under** the Debye temperature meaning that the heat capacity (C) is proportional to the absolute temperture to the power of 3 ($C \sim T^3$). **Over** the Debye temperature C is however more or less constant according to the law of Dulong and Petit[23]. The capacity is then roughly 25 J/mole K. The Debye temperature of Nickel is 450 K or 177 °C. The Debye temperature of Pd is 275 K or 2 °C. Thus both are over the Debye temperature in most of the tests in this report.

1 Mole of Nickel is 58.7 g and thus the C=25/58.7 x 1000 = 426 J/kg K
1 Mole of Palladium is 106 g and thus the C = 25/106 x 1000 = 236 J/kg K

For Carbon-graphite specifically ref [24] can be used. The capacity at 773 K or 500 °C is 1550 J / kg K

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[20] http://contrails.iit.edu/DigitalCollection/1957/WADCTR57-374part06.pdf (United States Air Force)
[21] http://www-d0.fnal.gov/hardware/cal/lvps_info/engineering/elementheatcap.pdf
[22] http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/debye.html
[23] http://hyperphysics.phy-astr.gsu.edu/hbase/thermo/dulong.html#c1
[24] http://www.osti.gov/bridge/servlets/purl/714896-UYYhLl/native/714896.pdf

For an 8.3 g mixture by weight of: C 4.18%, O 23%, Ni 5.4%, Si 0,21%, Zr 65%, Pd 0.86% at 500 °C we get:

Subst.	%	C	% · C
C	4,18%	1550	65
ZrO2	88,00%	643	565
NI	5,40%	426	23
Pd	0,86%	236	2
Sum	98,44%	Average	666 J/kg K
Weight	0,0083 kg		5,52 J/K

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