BAM
Bundesanstalt für
Materialforschung
und -prüfung

Sicherheit in Technik und Chemie

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EXPERIMENTAL STUDY ON THE IGNITION OF HYDROGEN CONTAINING ATMOSPHERES BY MECHANICAL IMPACTS

International Conference on Hydrogen Safety, Quebec, 2023

Enis Askar, Thomas Grunewald

Motivation - Example: Maintenance of Pressure Controlling Plants

Source: DGUV – DGUV Information 203-092

- Shutting off, venting and opening sections for maintenance and servicing work
- Purging of sections with nitrogen before opening usually very time-consuming
- Definition of explosion zones in which ignition sources must be excluded during maintenance work
- Possible measure of explosion protection: use of tools made of non-sparking-materials

Background
Mechanical Impacts as Ignition Source

In the case of mechanical impacts, ignition of explosive mixtures can occur due to separated particles of elevated temperature and on hot friction surfaces.

The ignition probability is mainly dependent from the:

- material pairing
- kinetic impact energy
- fuel gas – evaluation by explosion group (EG)

EG	MESG [mm]	MIC [mJ]
IIA	>0.9	≥0.8
IIB	0.5-0.9	0.45-0.8
IIC	<0.5	≤0.45

"Ignition sources generated by impact need not be considered as effective ignition sources if the impact velocity is less than 15 m/s and the maximum possible potential energy is less than the values given in Tables 4, 5, 6 and 7" (*ISO 80079-36:2016)*

EG	Non-sparking metals	Other materials
IIA	**125 J**	**20 J**
IIB	**125 J**	**10J**
IIC	**60 J**	**5J (H_2)**

Single impact energy limits for EPL Ga

Project „HySpark“ – Goals

Project Partner:

BG RCI
Berufsgenossenschaft
Rohstoffe und chemische Industrie

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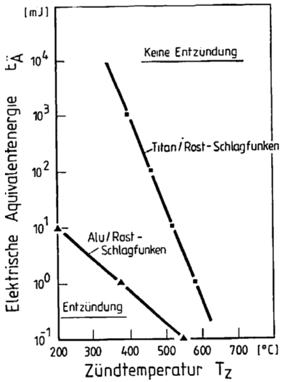
Key questions:

1. How effective are impacts as an ignition source for hydrogen depending on the (inhomogeneous) material pairing?
2. How does the effectiveness of mechanical impacts as an ignition source change when hydrogen is added to natural gas?

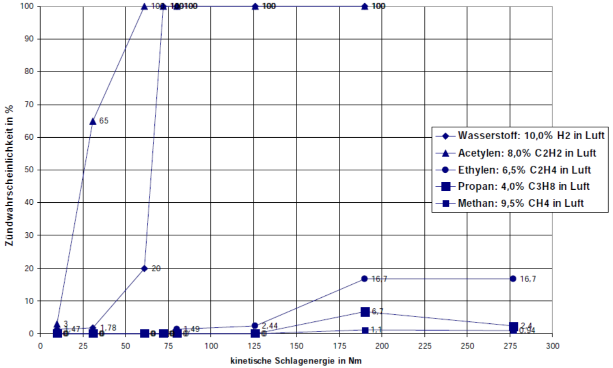
State of Knowledge – (1)

Bartknecht (1993)



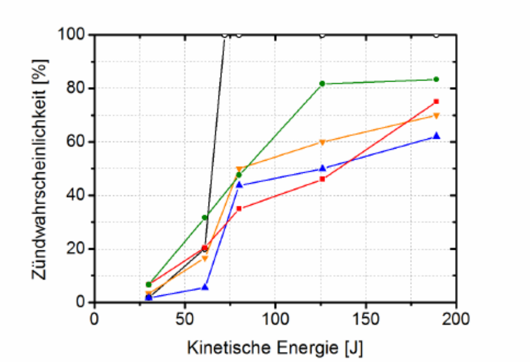
- Basic studies on influencing factors on ignition probability (IP)
- No systematic investigations on mechanical impacts

BAM research reports 279 & 292 (2007 & 2010)



- Reproducible test procedure for mechanical impacts
- Influence of kinetic impact energy on ignition probability for different gases
- Only impacts of unalloyed mild steel
- Worst Case: 10% H_2 in air

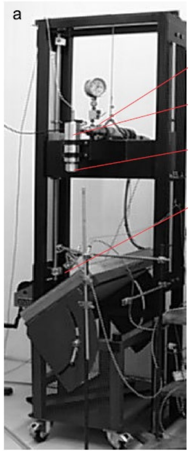
BAM research report Vh2104 (2015) – NAMES



- Variation of materials
- Limited to homogeneous material pairings and stainless steel
- Ignitions in hydrogen-atmospheres mainly at position of impact
- IP for H_2 higher than for acetylene with stainless steel

State of Knowledge – (2)

Proust et al. (2007) – MECHEX

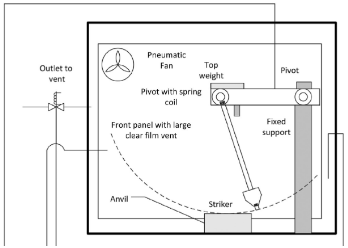


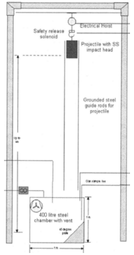
Cylindrical metal rods shooting on angled impact plated

Focus on determination of energy input. No experiments with H_2.

- ➢ Mainly „Hot-Surface-Igntion“ (in distinction to „Spark-Ignition“ and classical „AIT“)
- ➢ Importance of impact velocity in distinction to impact energy

Avril, Ingram et al. (2014-2020)





- → Background: atomic waste disposal with (→ contaminated surfaces)
- → Study on influence of impact conditions identifying impact velocity and impact geometry as important factors
- → Values in ISO 80079-36 rather worst-case scenarios
- → Experiments with much greater database necessary

Shebeko et al. (2015) –

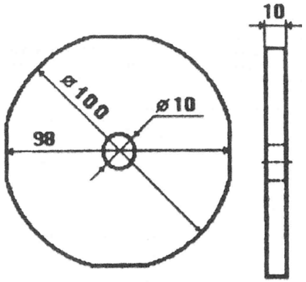
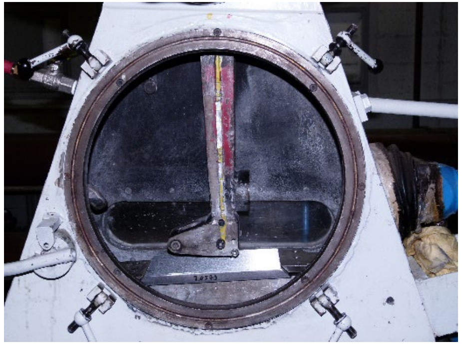


Fig. 2. Diagram of the rotating disk.

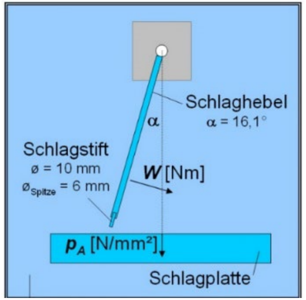
- → Combination of impact and friction sparks, IP from number of impact events
- → Investigation of IP for many material pairings, no impact energy defined
- → Theoretical consideration: Gas volume with D=δ necessary for ignition (corr. with S_U und MIE)
- → Importance thermal conductivity

Test apparatus for „HySpark“

Picture of impact spark apparatus



Schematic image



Video recording of impact

Normal velocity

1/4 velocity

High-speed recording of impact (Test 1 – ignition at impact location)

- material pairing: Steel 1.0579 vs. Steel 1.0579 (homogeneous)
- gas mixture: 10%H_2 + 1%CH_4 in air
- kinetic impact energy: 61 J

High-speed recording of impact (Test 2 – particle ignition)

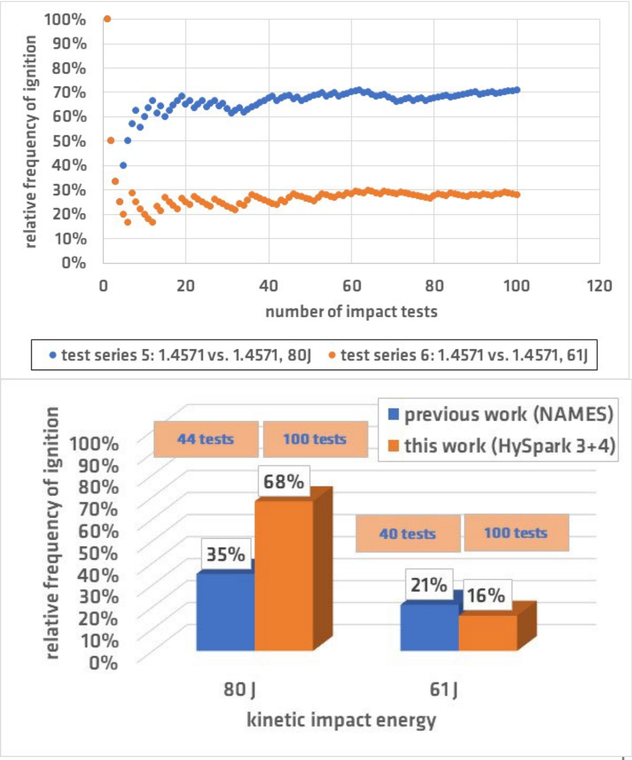
- material pairing: Steel 1.0579 vs. Steel 1.0579 (homogeneous)
- gas mixture: 10%H_2 + 1%CH_4 in air
- kinetic impact energy: 61 J
- **Repetition of test 1 without changing test parameters**

Pre-tests

6 pre-test series for method validation and determination of test parameters

- **100 tests per test series**
- 10% H_2 in air
- Kinetic impact energy of **61 J** (→ v = 8 m/s, F/A = 1,6 – 6,4 N/mm^2) (in reference to regulations, ISO 80079-36 etc.)
- Reproducibility of test results is generally given
- Homogeneuos material pairing 1.4571 only with slight differences to 1.4541 regarding ignition probability

Influence of number of impacts on releative frequency of ignition (top) and reproducibility of results (bottom)

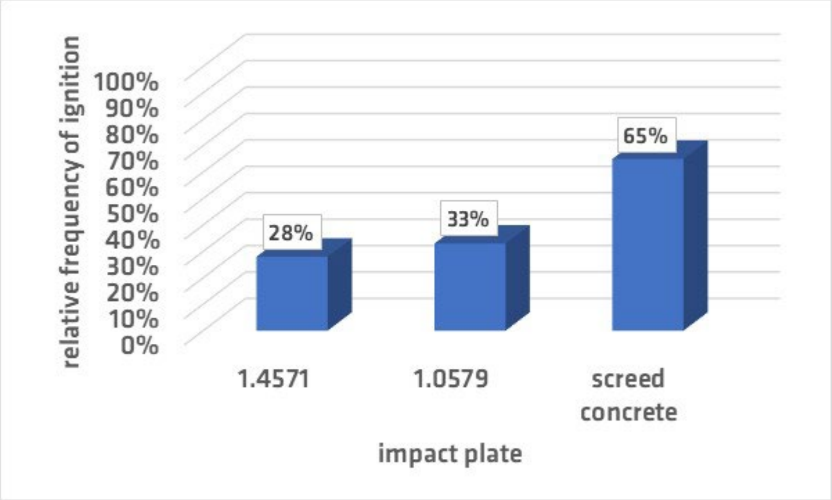


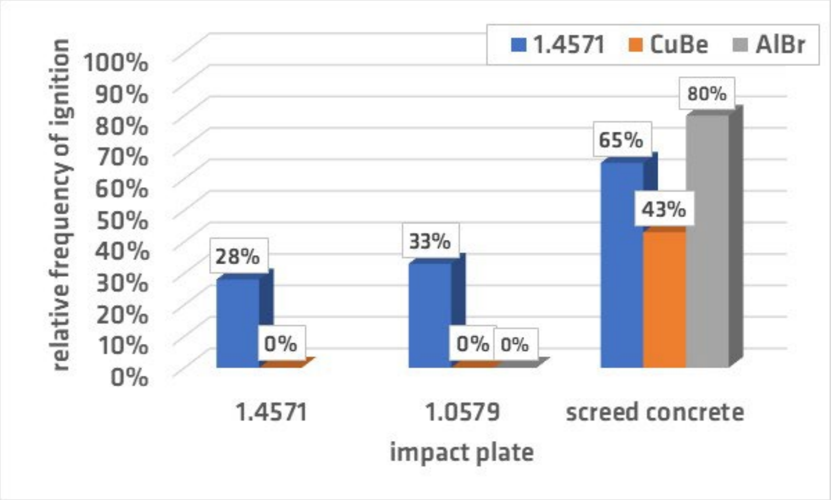
Material properties

Physical properties at 20 °C:

	unalloyed steel	stainless steel		Non-sparking, non-ferrous metals		concrete
	1.0579 1.0577	1.4541	1.4571	(2.1247) CuBe	2.0966 (AlBr)	Screed concrete
Thermal conductivity [W/(m*K)]	42 – 54	15	15	120 – 170	50	ca. 1,4
Spec. heat capacity [J/(kg*K)]	461	500	500	420	-	1000
Density [kg/dm3]	7.85	7.9	8.0	8.3	7.6	ca. 2,0-2,2
Elastic modulus [kN/mm2]	210 - 212	200	200	135	120	ca. 10-15

Ignition Probabilities determined in hydrogen containing atmospheres (61 J)

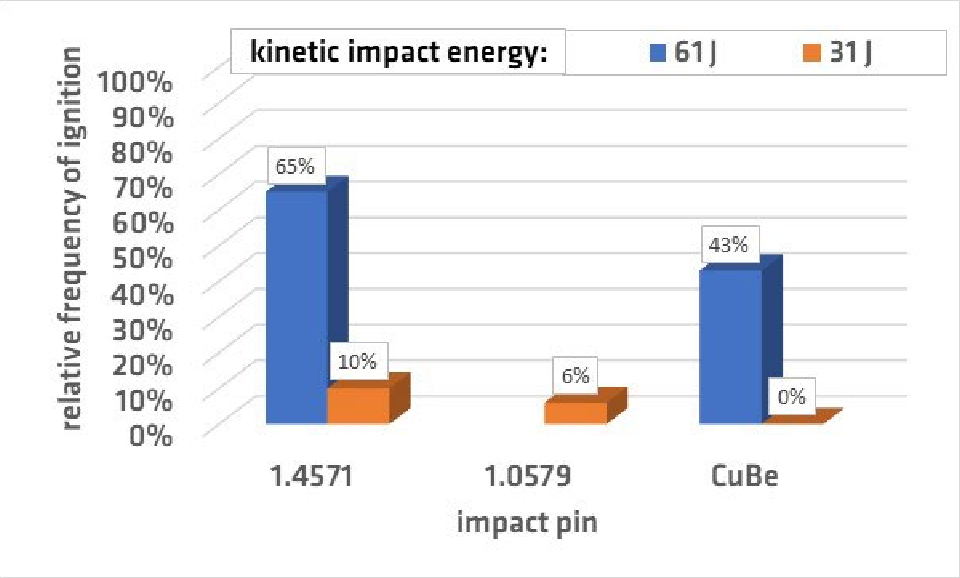




Conclusion: With impact pins made of stainless steel (1.4571) only slight influence of material of impact plate (1.4571 vs. 1.0579). With impact plate made of concrete relative frequency of ignition increases clearly

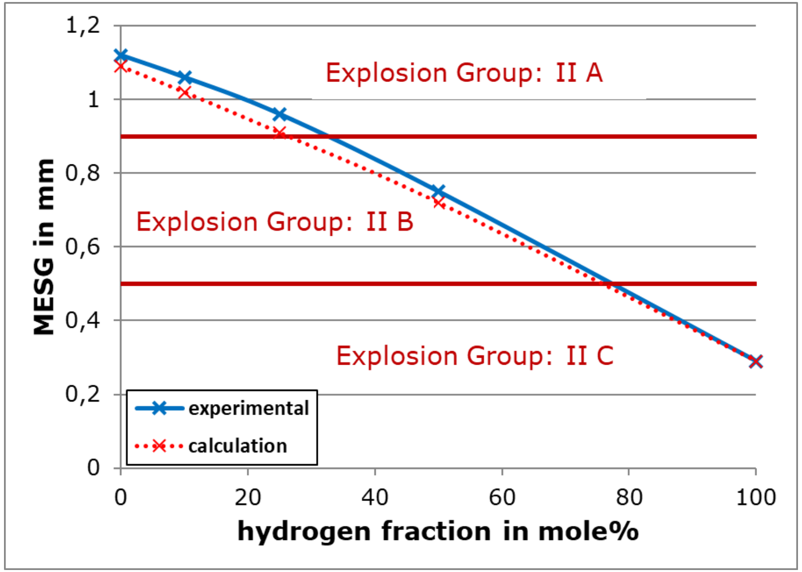
Conclusion: With impact pins of non-ferrous materials the ignition frequency is still high for impacts against concrete (even higher than for acetylene). Not considered in ISO 80079-96.

Ignition Probabilities determined in hydrogen containing atmospheres (31 J)



<u>**Conclusion:**</u> Ignition by impacts against concrete is prevented by by using the non-sparking materials and reducing the kinetic impact energy to 31 J. With ferrous metals ignition can not be prevented by reducing the kinetic impact energy to 31 J.

Hydrogen-natural-gas-mixtures: explosion groups



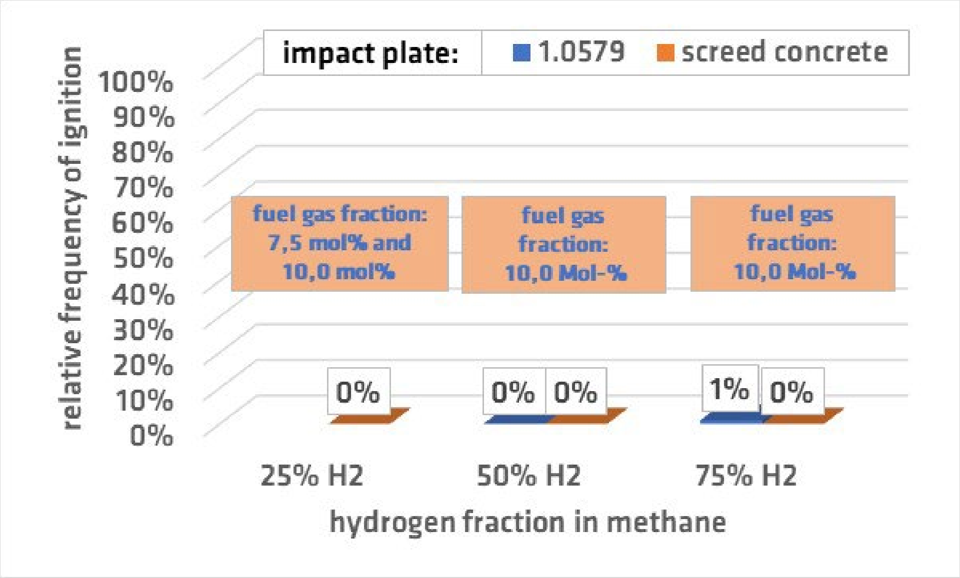
Calculation according to CHEMSAFE/PTB-correlation

Allocation to explosion groups (EG) is done according to maximum experimental safe gap (MESG) or minimum ignition current (MIC):

EG	MESG [mm]
IIA	>0.9
IIB	0.5-0.9
IIC	<0.5

Conclusion: The MESG tends to decrease linearly with increasing hydrogen fraction.

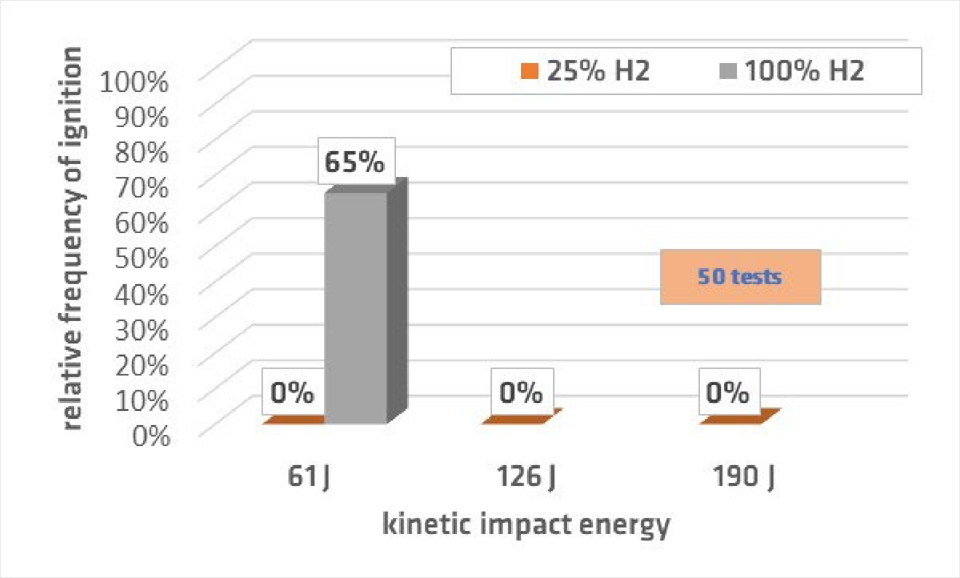
Ignition Probabilities for H_2-NG-mixtures



- 1.4571 pin vs. different plates (1.0579 and concrete)
- kinetic impact energy 61 J

Conclusion: Only in mixtures with a hydrogen content of 75% in natural gas was ignition observed at all. This corresponds approximately to the fraction above which the mixture would have to be assigned to explosion group IIC (according to the MESG or MIC).

Ignition Probabilities for mixtures of 25% H_2 methane with increasing kinetic impact energy



material pairing: 1.4571 vs. concrete

Target: For a practical mixture of 25% hydrogen in methane, at what impact energy can a difference from 100% methane be detected for a material pairing that is as "unfavorable" as possible?

Conclusions

- By using tools of non-ferrous metals effective ignition of H_2 containing atmospheres can be prevented (compared with tools of steel). This may also be related to the high thermal conductivity or lower hardness of the nonferrous metal.

- Still, for impacts against screed-concrete, the kinetic impact energy must be further reduced compared to impacts against metals. Adaption of regulations (ISO 80079-36 etc.) might be sensible

- H_2 seems to be easier to ignite than acetylene when ignition occurs mainly at the hot friction surface in contrast to impacts with a high number of separated particles of increased temperature. MIE alone does not fully cover the ignition sensitivity.

- For mixtures up to 25% H2 in methane no difference was observed at all compared to pure methane regarding the ignitability by mechanical impacts. A difference was observed for mixtures from 75% H2 in methane.

- Other material pairings, involving materials like light metals, light metal alloys are still not studied very well

Thanks! Any Questions?

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Comparison of material compositions

Compositions as a percentage of mass:

	C	Si	Mn	P	S	Cr	Ni	Mo	Ti	Cu
1.0579 1.0577	≤0.22	≤0.55	≤1.6	≤0.03	≤0.03	-	-	-	-	≤0.55
1.4541	≤0.08	≤1.0	≤2.0	≤0.045	≤0.03	17.0-19.0	9.0-12.0	-	≤0.7	-
1.4571	≤0.08	≤1.0	≤2.0	≤0.045	≤0.03	16.5-18.5	10.5-13.5	2.0-3.0	≤0.7	-

	Be	Co+Ni+Fe	Cu	other
CuBe	1.5-2.3	≤1.2%	≥95.5	≤1.0

	Al	Ni	Fe+Mn	Cu	other
AlBr	10-12	4-6	≤6	≥75	≤1

	aggregate	cement	water	Fluxing agent
screed concrete	81 (containing 5% corundum EKF 10 and 95% quartz sand)	12	6.8	0.2

Bestimmung der Schlageenrgie

Die Schlagenergie wurde als Summe aus potentieller und kinetischer Energie bestimmt:

$$E_{ges} = E_{pot} + E_{kin}$$ mit $$E_{pot} = m * g * h$$

und $$E_{kin} = \frac{1}{2} * m * v^2$$ bzw. $$E_{kin} = \frac{1}{2} * I * \omega^2$$ (Rotationsbewegung)

mit: I = Massenträgheitsmoment
ω = Winkelgeschwindigkeit

Die (mittlere) Winkelgeschwindigkeit wurde mit Hilfe von Lichtschranken durch die Messung der Zeit im Abstand von ca. 25 mm unmittelbar vor dem Aufsetzen des Schlaghebels bestimmt:

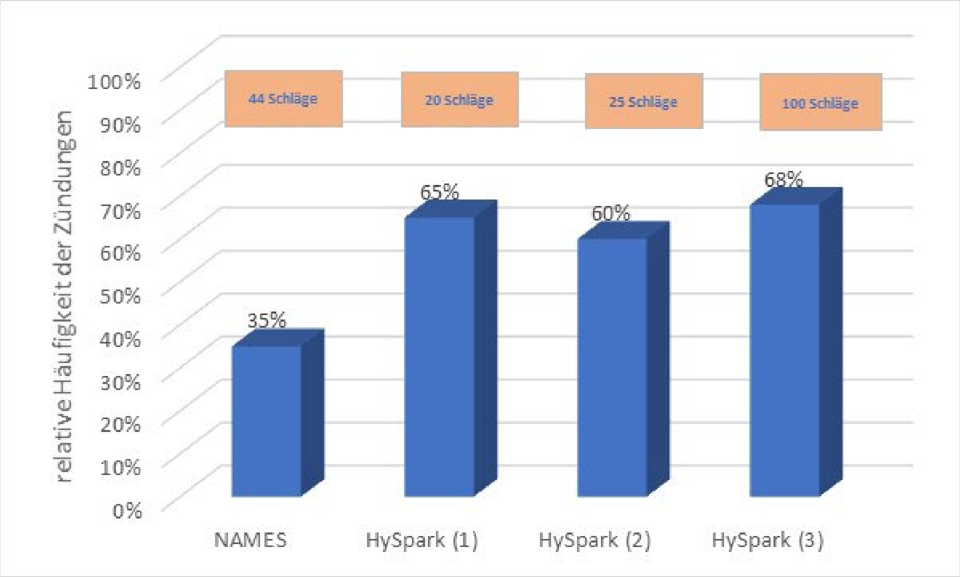
$$\omega = \frac{\varphi}{t}$$

mit: φ = Bogenmaß, t = gemessene Zeit bis zum Durchschreiten der Lichtschranken durch den Schlagbolzen

Das Massenträgheitsmoment des Schlaghebels (bezogen auf die Drehachse) wurde durch einen Ansatz von „GIECK“ bestimmt aus Masse, Massenschwerpunkt, einfacher Schwingdauer des Schlaghebels, die jeweils experimentell bestimmt worden sind.

Methodenvalidierung

Zur Validierung der Reproduzierbarkeit wurden Versuche aus dem NAMES-Projekt wiederholt

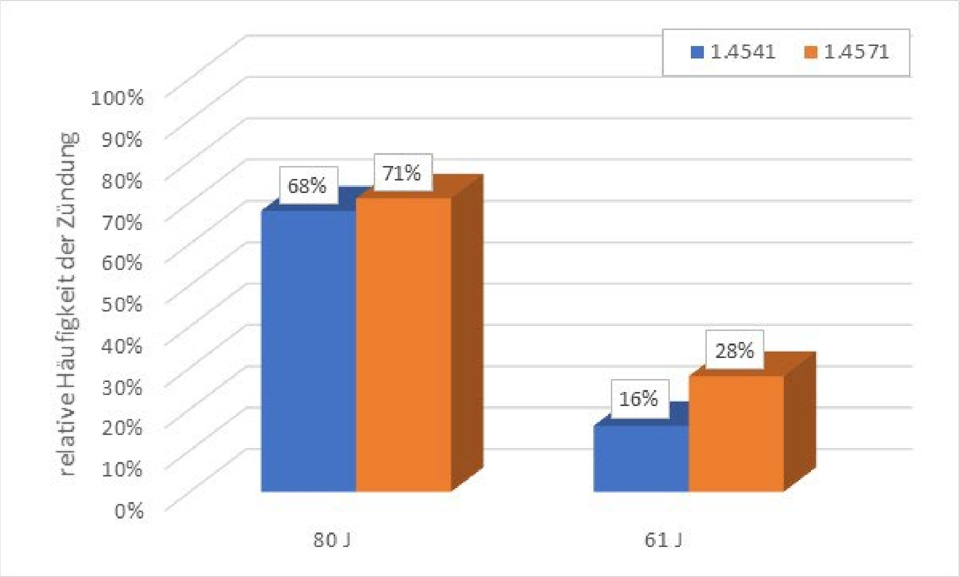


- Es wurden die relativen Häufigkeiten der Entzündung bestimmt
- Homogene Materialpaarung: Stahl 1.4541 vs. Stahl 1.4541
- Schlagenergie 80 J

Fazit: Größere Abweichung zum Ergebnis aus dem NAMES-Projekt, aber hohe Reproduzierbarkeit beim Vergleich der drei neuen Versuchsreihen

1.4541 vs. 1.4571

Bei Schlagvorgängen mit homogenen Materialpaarungen mit den Stahlsorten 1.4541 und 1.4571 treten nur geringe Unterschiede bzgl. der Zündwirksamkeit auf



- Homogene Materialpaarungen: Stahl 1.4541 vs. Stahl 1.4541 und Stahl 1.4571 vs. Stahl 1.4571
- Schlagenergie 61 J und 80 J
- Anzahl der Schläge je Versuchsreihe: 100

Fazit: Für die homogene Materialpaarung mit der Stahlsorte 1.4571 war die relative Häufigkeit geringfügig höher gegenüber der Stahlsorte 1.4541 trotz sehr ähnlicher Materialeigenschaften. Für die Beurteilung der Signifikanz dieses Unterschieds wären mehr Versuche erforderlich.

Ergebnisse Projekt NAMES (2015)

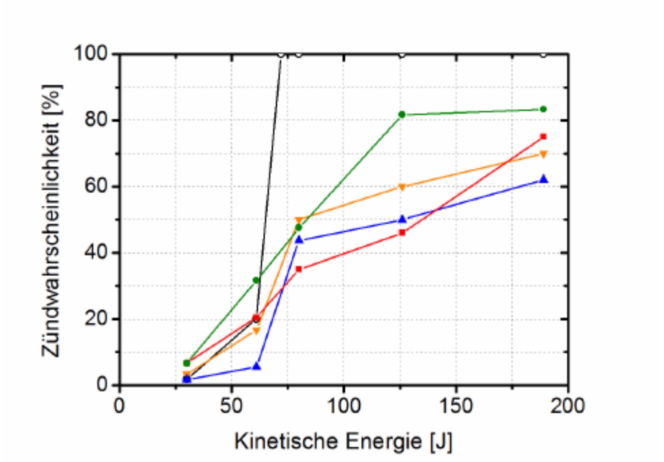


Abb. 5: *Zündwahrscheinlichkeit eines Wasserstoff/Luft-Gemischs mit 10,0 Vol.-% Wasserstoff durch mechanische Schlagvorgänge mit den Edelstahlsorten 1.4307 (▼, orange), 1.4313 (▲, blau), 1.4462 (●, grün) und 1.4541 (■, rot) im Vergleich zu Baustahl 1.0570 (○, schwarz) (Grunewald et al., 2010) in Abhängigkeit von der maximalen Schlagenergie. Die Verbindungslinien zwischen den Punkten dienen als Orientierungshilfe.*

Abb. 4: *Versuchsapparatur zur Durchführung von Schlagvorgängen mit aufgestellter Hochgeschwindigkeits-IR-Kamera zur Dokumentation der Versuche und zur Bestimmung des Zündortes.*

Forschungsbericht BAM 279 (2007)

- Untersuchte Werkstoffpaarung: ferritischer, unlegierter und ungehärteter Stahl St52 (Werkstoffnummer 1 .0570 – St52-3/S355J2G3), Kohlenstoffgehalt von max. 0,22 %

- Wasserstoff/Luft-Gemische:
  - W = 190 Nm (zündwilligstes Gemisch, 10,0 Mol-%) → Zündwahrscheinlichkeit: 100%

- Methan/Luft-Gemische:
  - W = 190 Nm (zündwilligstes Gemisch, 9,5 Mol-%) → Zündwahrscheinlichkeit: 1,1%

- Bei hoher Wärmeleitfähigkeit wird die Wärme schneller abgeführt, daher gibt es weniger oxidierte Stahl-Schlagfunken. Bei W=190 Nm: bis BG 45 Mol-% → 100% oxidierte oder geschmolzene Partikel unabhängig vom Edelgasanteil (sowohl bei Ar als auch bei He)

Ergebnisse Projekt NAMES (2015)

- 4 verschiedene Edelstahlsorten (mit Chromanteilen zwischen 12% und 23%), Hochgeschwindigkeits-Infrarotkamera (ThermoVision SC4000, FLIR)

- Schläge mit Edelstahlsorte 1.4462 (22,5% Chrom) bei Wasserstoff am zündwirksamsten, aber deutlich niedriger als bei Baustahl, unterhalb von 80 J kein Unterschied zu Baustahl

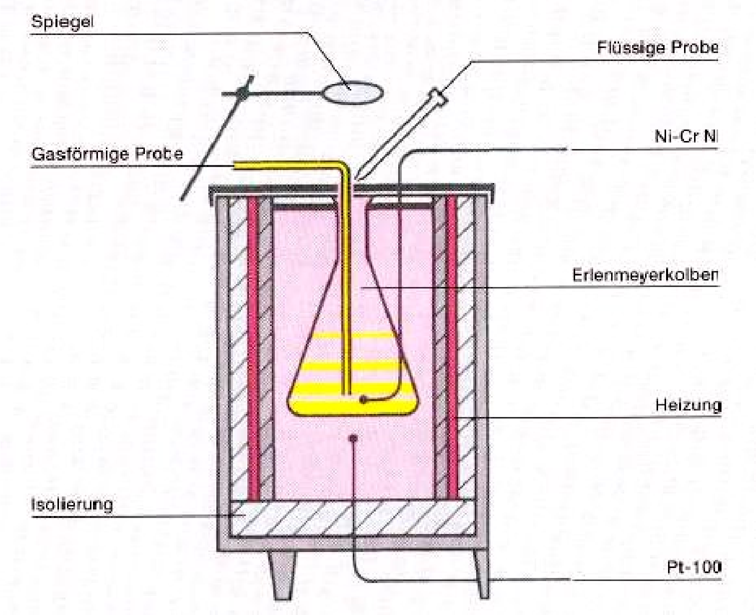
- Gasgemisch wird beim Wasserstoff anders als bei unlegiertem Baustahl fast ausschließlich durch heiße Reibstellen des Bolzens oder der Platte gezündet

- Schlagvorgänge mit funkenarmen Edelstählen können auch zündwirksam sein (i.d.R. durch heiße Reibfläche). Schläge im Wasserstoff/Luft-Gemisch waren hier am zündwirksamsten (vgl. mit Acetylen, Ethen und Propan), obwohl ZT von H2 hoch ist. Grenzspaltweite auch ungeeignet als Kriterium für Zündwirksamkeit von Schlagfunken.

- Wärmeleitfähigkeit des Stahls ist ein wesentlicher Faktor für Zündwahrscheinlichkeit → heiße Reibflächen bei Bewertung des Zündrisikos berücksichtigen

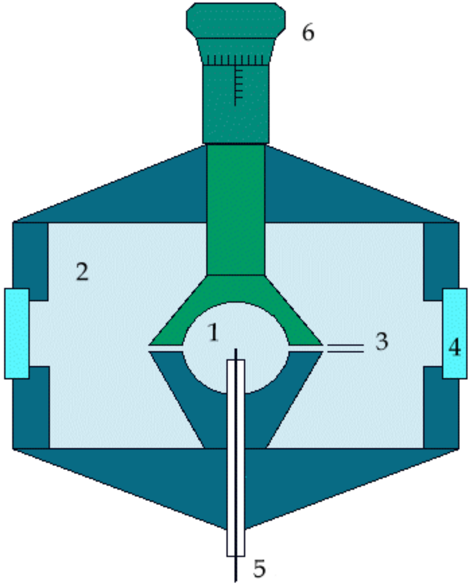
- inhomogene Werkstoffpaarungen bisher nicht berücksichtigt

Auto Ignition Temperature (AIT) and Temperature Class Classification



Temperature Class	AIT In °C
T1	> 450
T2	300 – 450
T3	200 – 300
T4	135 – 200
T5	100 – 135
T6	85 – 100

Maximum Experimental Safe Gap (MESG) and Explosion Group (EG) Classification



EG	MESG [mm]	MIC [mJ]
IIA	>0.9	≥0.8
IIB	0.5-0.9	0.45-0.8
IIC	<0.5	≤0.45

Explosion group (EG) classification either according to the maximum experimental safe gap (MESG) or the minimum ignition current (MIC) related to methane (=1). The MESG correlates with the MIC.

1 - inner explosion chamber
2 - outer explosion chamber
3 - gap
4 - window
5 - ignition source
6 - set screw

Motivation
Regulatory Framework

ATEX Directive 1999/92/EC art. 3:

"… the employer shall take technical and/or organizational measures … , in order of priority and in accordance with the following basic principles:"

- Avoid explosive mixtures
- Avoid ignition sources
- Mitigate consequences of explosions

Typical ignition sources to be considered according to EN 1127-1:

1. **Hot surfaces**
2. **Flames and hot gases**
3. **Mechanically generated sparks**
4. **Electrical equipment (except stray current)**
5. **Stray electric current, cathodic corrosion protection**
6. **Discharge of static electricity**
7. Lightning
8. Electromagnetic fields
9. Electromagnetic radiation
10. Ionising radiation
11. Ultrasonics
12. **Adiabatic compression and shockwaves**
13. **Exothermic reactions**