

Assessment for Hydrazine detonability during priming system activities

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ABSTRACT

Since the 1960s, hydrazine has been one of the classical propellants used on spacecraft chemical propulsion systems. This propellant is known to have a susceptibility to detonate when compressed at certain conditions of speed and compression ratio. However, there has always been controversy to establish where the threshold for hydrazine detonability is, due to the high number of parameters affecting the results, the variability of the test conditions (e.g. test setups, initial conditions, etc). This paper intends to help better understand hydrazine detonability, define the conditions where this phenomenon is triggered and proposes a logic and methodology to resolve this problematic henceforward.

ACRONYMS

ESA – European Space Agency

ESTEC – European Space Research and Technology Centre

HEM – Homogeneous Equilibrium Model

ID – Internal Diameter

NCG – Non condensable gas

SS – Stainless Steel

UN – United Nations

WSTF – White Sands Test Facility

VARIABLES

$A_{\text{heat exchange}}$ [m^2] – Instantaneous heat exchange area between the gas cavity and the pipe at maximum surge pressure peak (see red line in Figure 2).

C_X [-] – Correction factor of X parameter. See subscripts below:

CG – Cavity gas

PG – Push gas

M – material catalytic effect

G – grade of the propellant

D – Bottom diameter

$C_{p_{\text{gas}}}$ [$\text{J}/(\text{kg}\cdot\text{K})$] – Specific heat of the gas at T_0

D [m] – Internal pipe diameter

Df [J/m^2] – Detonation factor

$Df_{\text{reference}}$ [J/m^2] – Reference detonation factor

$E_{\text{reference}}$ [J/mole] – Activation energy of the reaction between hydrazine and the construction material used as reference case

E_{material} [J/mole] – Activation energy for the reaction between hydrazine and the construction material

I – [kg/m^2] - Inertia

$k_{0,\text{reference}}$ [$\text{mole}/(\text{s}\cdot\text{m}^2)$] – pre-exponential factor of the reaction between hydrazine and the construction material used as reference case

$k_{0,\text{material}}$ [$\text{mole}/(\text{s}\cdot\text{m}^2)$] – pre-exponential factor of the reaction between hydrazine and the construction material

L_{peak} [m] – Instantaneous length of the theoretical cylindrical ideal gas cavity at maximum pressure surge peak assuming a piston analogy (see Figure 2)

m_{gas} [kg] – Mass of gas available in the cavity gas (no gas absorption in the liquid)

MW [g/mole] – Molecular Weight

R [$\text{J}/(\text{mole}\cdot\text{K})$] – Ideal Gas constant (8.314)

T_0 [K] – Initial temperature of the gas cavity

T_1 [K] – Initial temperature of liquid test fluid

T_{ad} or $T_{\text{adiabatic}}$ [K] – Theoretical adiabatic temperature of the gas at maximum peak surge pressure.

P_0 [Pa] – Initial pressure of the gas cavity

P_1 [Pa] – Initial pressure of liquid test fluid

P_{peak} [Pa] – Maximum peak surge pressure

γ_{gas} [-] – Heat capacity ratio

INTRODUCTION

Hydrazine Rapid/Adiabatic compression sensitivity may occur when hydrazine flows into initially empty (e.g. filled with gas) propellant distribution lines resulting in a temperature increasing collapsing bubble sufficient to initiate detonation. This phenomena could be reproduced at given conditions (e.g. given test setup, pressure and temperature conditions). However, when the test setup or key parameters were modified, different detonation thresholds were found. This has historically been difficult to understand due to the large number of

variables which may influence the results and therefore a pass/fail criteria has been difficult to define.

This paper performs an extensive and critical bibliographical survey on hydrazine detonability/priming investigation and proposes a flow logic and a simplified mathematical model to assess hydrazine detonability. The proposed model could be used to assess the risk of hydrazine detonation when designing new propulsion systems.

DATA QUALITY

Schmidt ([1]) performs a detailed discussion over different test setups used for the characterisation of hydrazine adiabatic detonation. Test setups did evolve during the characterisation of hydrazine detonability. One major challenge was the difficulty to achieve repeatable results while keeping the test setup as simple and cost effective as possible.

A total of four different test setups are described, see below:

Test Setup	Cost/Simplicity	Test repeatability	Data availability
Model Piston Apparatus	++	---	---
U-tube Apparatus	++	-	+++
Diaph.-Straight Tube Apparatus	-	++	-
WSTF Straight-Tube Apparatus	-	+++	+++

Table 1. Test setup comparison

WSTF straight tube apparatus is the test setup which shows the best test data quality due to a good compromise of test repeatability and data availability ([1], [2]) and a test setup flexibility to assess multiple test conditions. The test has been repeated using an inert fluid simulant (i.e. water) and hydrazine to identify the hydraulic pressure peak which triggers hydrazine decomposition.

Figure 1 shows similar surge pressure peak behaviours when all fluids are stable and a divergence when hydrazine starts to decompose.

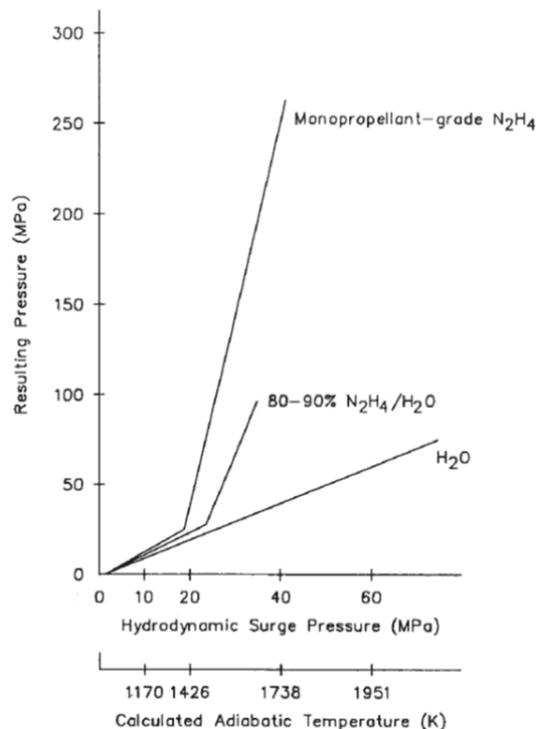


Figure 1. Hydrazine detonability [2]

Most test data and main reference in this paper is made to the WSTF straight tube apparatus.

In addition, several adiabatic compression tests have been performed using either flight representative pipe manifolds or WSTF-like test setups (e.g. [3], [4]) and added to this paper as test data for validation.

Based on Table 1, attention shall be paid to the data source for quality discrimination. The following order is proposed:

$$\textcircled{1} > \textcircled{2} > \textcircled{3} > \textcircled{4}$$

- ① WSTF Straight-Tube Apparatus (e.g. [2])
- ② Diaphragm-Straight Tube Apparatus (e.g. [5])
- ③ U-tube Apparatus (e.g. [5])
- ④ Model Piston Apparatus (e.g. [6])

METHODOLOGIES TO RESOLVE ADIABATIC DECOMPOSITION PROBLEMATIC

As far as practically possible, stress hydrazine detonability limits shall be avoided. Should this not be possible, three approaches for the risk assessment of hydrazine detonability are discussed below:

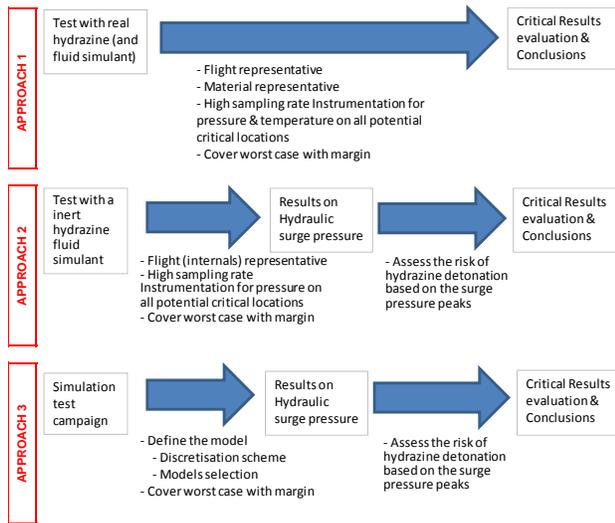


Figure 2. Flow Logic Methodologies

TEST CAMPAIGN WITH REAL HYDRAZINE

Perform a test campaign with real hydrazine propellant (i.e. same grade as for flight) using a configuration which is flight representative: including pipe layout, flow passages, representative flight-like hardware, dead ends, etc. The objective is to capture the critical pressure and temperature transients (i.e. partial hydrazine decomposition).

Construction materials for the test setup and preparation shall be flight representative.

Later the test shall be repeated with a hydrazine simulant inert fluid (i.e. water) in order to determine if surge pressure peaks are caused by a hydraulic shock or an initiation of chemical decomposition of hydrazine.

TEST CAMPAIGN WITH A HYDRAZINE SIMULANT FLUID

Perform a test campaign with a hydrazine propellant inert simulant only (e.g. demineralised water) using a configuration which is flight representative: including pipe layout, flow passages, fluidically representative hardware, dead ends, etc.

The objective is to capture hydrodynamic surge pressure transients. Temperature of the gas and liquid prior the test shall be recorded.

Construction materials shall be compatible with the simulant fluid. It does not need to be flight representative if no effect on the fluid dynamics due

to change of construction material can be demonstrated (e.g. change of strength and stiffness).

At the conclusion of the test campaign, an assessment is to be performed on the hydrazine detonability risk based on the test results using the simulant fluid. In the frame of this paper, one possible approach is presented.

SIMULATION CAMPAIGN

Perform a simulation campaign using a validated tool to resolve priming with a hydrazine fluid simulant in two phase with pressure transients of this nature and later assess the risk for detonation (similarly as it is performed for the test campaign with a fluid simulant). This assumes that the numerical tool is able to simulate hydraulic pressure peaks (e.g. no chemical reaction).

Prior to the initiation of any simulation campaign, the proposed tool shall demonstrate a full validation for this type of problems. This includes test cases with different test setups, test initial conditions and complex pipe manifolds which covers any potential worst case for the real case. The validation shall also encompass fluid properties verification, assumptions made for the definition of the models and discretisation schemes.

ESA-ESTEC has EcosimPro ([11]) as main reference tool for fluidic transients and steady-state simulations. Some early steps are being performed for the validation of priming cases with EcosimPro.

GENERAL CONSIDERATIONS FOR TESTING

It is of key importance to identify and properly instrument critical locations for sudden pressure transients. Typical locations can be:

- Dead ends
- Flow constrictions (e.g. orifices, reducers, valves)
- Tees and bends
- Materials not rated for long term compatibility.
- etc

Also, on all test setups, it is of key importance to verify the test repeatability and perform at least three trials at exactly the same conditions.

The data sampling rate shall be assessed. Often sampling rates of 10 kHz should be sufficient for most applications. For cases the liquid front is discharge to vacuum, larger sampling rates may be needed.

Define test cases which envelope the worst case conditions. Typically, higher risk of detonation may be found on cases with higher hydraulic pressure surge, larger gas/vapour slugs, lower or unknown material chemical compatibility and/or initial higher propellant temperature.

GENERAL CONSIDERATIONS FOR SIMULATIONS WITH ECOSIMPRO

Knowing the assumptions on which the numerical tool is based is fundamental to properly understand and assess the computed results when a priming simulation is performed.

In case of the EcosimPro tool, the thermodynamic fluid properties are based on the so called Homogeneous Equilibrium Model (HEM). This model assumes a homogeneous mixture with uniform temperature, where the main fluid computed as real fluid occupies the entire volume, while the so called non-condensable gas (NCG) occupies the same volume as the real fluid vapour at saturated state, according to the Gibbs Dalton law. Furthermore, the NCG is insoluble in the liquid phase of the real liquid, which means that the NCG, if present, is always in gas state and absorption is not yet possible. [The fluid phase is automatically calculated. The homogeneous equilibrium model is used to calculate a real fluid under two phase conditions with or without a non-condensable gas mixture. Due to this characteristic of the two-phase model, the speed of sound obtained numerically is highly affected by the presence of the NCG. In EcosimPro, a few nodes in a pipe element are enough to calculate the pressure surges during water hammer in single phase flows. With NCG, and due to the assumptions of the HEM, the solution requires a higher number of nodes compared to a single phase waterhammer flow. In fact, the events taking place inside the node will not be distinguished by the software. This means that if the liquid front is crossing a node, the solution will be

a liquid + gas mixture inside that node. This error can only be reduced by adding more nodes to the pipe element. Of course, together with the number of nodes, the numerical schemes used might also have an influence on the final solution.

Other important considerations must be applied when complex pipelines systems are simulated, especially regarding the numerical discretization of each pipe. The number of nodes in a system made of several tubes having each one different lengths and diameters, is a complex parameter to manage.

Thus it has been established rules for undertaking parametric studies on the number of nodes:

- Intuitive rule: aiming to set the maximum number of nodes in the tubing where the results are to be focused (or at the place where the experimental data are available). This should be followed in the first phase of the work.

- Rule SQRT(Inertance): this rule is coming from some considerations about the hydraulic impedances that is defined as the square root of the inertance divided by the capacitance. The number of nodes chosen is such that each tube has a similar value of $\text{SQRT}(L/A)$ divided by the number of nodes per tube.

- Rule (Inertance): this rule is coming from some considerations about the momentum equation. According to the Streeter Handbook of fluid dynamics [12], the inertance is defined as the product of the density by the length and divided by the section area, for a small element ∂L

$$I = \rho \frac{\partial L}{A} \quad (\text{eq.1})$$

and for a composite pipeline

$$I = \rho \sum_k \frac{\partial L_k}{A_k} \quad (\text{eq.2})$$

In order to keep an independence between the geometrical data and the fluid to be used in the experiments, we call here “Inertance” the substantive part of the above definition, that is $\partial L / A = I / \rho$. The number of nodes is chosen such that each tube element have similar value of (dL/A) .

DISCUSSION OF THE VARIOUS METHODOLOGIES

Clearly, a test campaign using the real propellant in a fully representative flight configuration and monitoring temperature and pressure on all critical location (see below) is the approach which best minimises any risk of hydrazine adiabatic

decomposition and most accurately identifies hydraulic surge pressure peaks. However, a test campaign of these characteristics may incur in high costs and schedule limitations due to safety, procurement of long lead items (e.g. flight components, propellant) and the limited sites where tests of this nature can be performed.

A more cost effective alternative could be a test campaign using a simulant. For an adequate assessment, a good correlation between hydrazine detonability risks and maximum flight expected temperatures and a simulant hydraulic pressure peaks shall be demonstrated. This paper analyses the existing data. Regardless of the methodology used, it is the authors' view that this approach could be viable to assess hydrazine detonation for a large number of propulsion systems.

Finally, the third approach relies on the simulation campaign with a validated code. Specifically for EcosimPro has shown good results on simple pipe manifolds and vacuum in the gas cavity (e.g. effectively priming with one fluid only). Once a NCG is inserted, EcosimPro tends to overestimate the pressure peak (e.g. the larger the amount of NCG, the larger overestimate) due to the HEM model.

To anchor the EcosimPro results and prove its reliability for future systems, more flight representative tests must be used for validation.

HYDRAZINE DETONABILITY LIMITS KEY VARIABLES

In the past, several attempts have been proposed to characterise the risk of hydrazine adiabatic detonation. The key parameters that have been historically used are the pressurisation rate and the compression ratio of the gas bubble at the point of maximum peak pressure. Other authors (e.g.[1]) have proposed the velocity of the liquid front during compressibility.

PRESSURISATION RATE

The main logic being the higher the pressurisation rate, the lower the time to evacuate the heat generated due to gas bubble compression and therefore local

“hot spots” in contact with hydrazine leading to detonation. However, Briles ([5]) found that in order to achieve detonation at higher pressurisation rates (with the U-tube test setup with the gas cavity filled in nitrogen), the initial hydrazine temperature had to be increased. This is to this date not fully understood.

COMPRESSION RATIO

This refers to the compression ratio of the gas cavity between the instant of maximum pressure peak and the initial pressure. Similarly to the pressurisation rate, higher compression ratios would exhibit a higher tendency for hydrazine detonation. However, this may be dependent on the initial gas cavity pressures. For example, Bunker ([2]) show no hydrazine decomposition at close-to-vacuum cavity conditions with compression ratios in excess of $2 \cdot 10^7$ whereas filling the gas cavity pressure up to 85.5 kPa, a pressure surge of 170 bar was sufficient to initiate hydrazine decomposition (i.e. compression ratio of 198).

LIQUID FRONT VELOCITY

The complexity to measure this parameter and the lack of data available makes the monitoring of the liquid front velocity less attractive. Could this be reliably achieved, the surge pressure peak due to the hydraulic effect could be assessed and therefore there would not be a need to repeat the same test with hydrazine and a fluid simulant.

PARAMETERS DISCUSSION

The methodology proposed uses as main key variable a new parameter named *Detonation factor* which is mainly derived from the compression ratio and does not take into consideration the other parameters described above. The main rationale is summarised below:

- As discussed above, the WSTF Straight-Tube Apparatus and/or flight-like configuration test setup is being used due to the quality of the data. In all cases, pressure peaks were measured and therefore only compression ratios could be derived. No pressurisation rate was measured.
- Data availability and evaluation of affecting parameters: most existing data have been obtained using compression ratio criteria.

- Other test setups monitoring pressurisation rates (e.g. U-tubes) showed results that are counter-intuitive or difficult to explain (e.g. higher pressurisation rates needed for detonation when increasing temperature)

HYDRAZINE ADIABATIC DETONATION MODEL

A very simplified model is proposed. The model assumes a cavity filled with gas and it is separated from a pressurised liquid by a barrier (i.e. a valve). The valve is actuated and the liquid front compresses the gas cavity downstream (e.g. perfect gas). The gas cavity therefore increases in temperature due to compression. The temperature increase (in direct contact with hydrazine) may generate propellant chemical decomposition or even detonation. See schematic as follows:

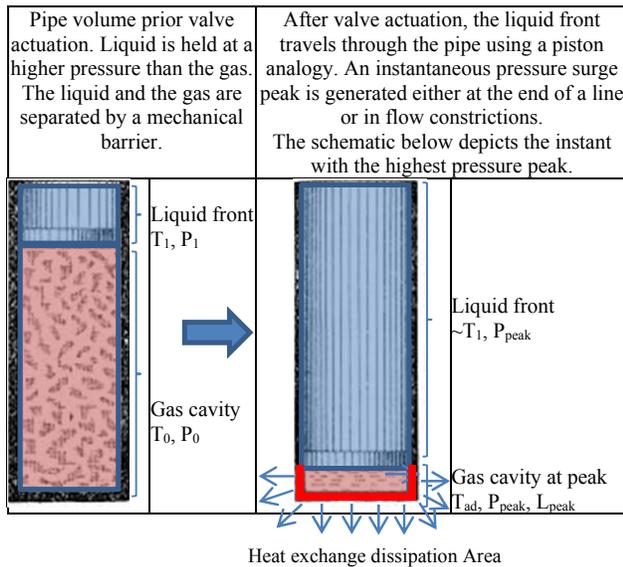


Figure 3. Detonation model piston analogy

The nomenclature of Df (i.e. detonation factor) has been used to denominate the risk of hydrazine detonability. The higher the number, the higher the risk. The main equation is shown below:

$$Df = C_M \cdot C_D \cdot C_G \cdot C_{CG} \cdot C_{PG} \cdot Df_{reference} \quad (\text{eq.3})$$

The detonation factor is calculated based on a reference case (i.e. $Df_{reference}$) and then corrected by several C_x or correction factors.

More parameters which could affect adiabatic detonation could be added (e.g. valve opening time), a comprehensive list is provided in [1]. However, the mentioned list does not make a distinction between parameters affecting what is a pure hydraulic problem, and by extension detonation, and parameters which affect the chemistry of hydrazine. Equation 3 separates the hydraulic aspects (i.e. all contained in $Df_{reference}$) and other affecting parameters (i.e. C_x).

REFERENCE CASE

The reference case is calculated based on a series of fixed parameters namely:

- Reference fluid: demineralised water at 300K
- Reference material: SS304L
- Pipe diameter: 1/2" (ID = 10.9 mm)
- Hydrazine Monopropellant grade detonability limits
- Push Gas: Nitrogen
- Cavity Gas: Nitrogen

The reference fluid is demineralised water in view of a methodology approach based on the prediction of pressure transients of a hydrazine inert simulant fluid (via test or eventually via simulation).

When a new case (e.g. using other fixed parameters) needs to be evaluated, then empirical correction factors and $Df_{reference}$ shall be calculated. Otherwise the correction factor is equal to unity. The correction factors are:

- Catalytic effects of the material (C_M)
- Pipe diameter (C_D)
- Hydrazine propellant grade (C_G)
- Push Gas (C_{PG})
- Cavity Gas (C_{CG})

Correction factors have been calibrated in accordance to the available test data cited in Table 3.

The $Df_{reference}$ is calculated as follows:

$$Df_{reference} = \frac{m_{gas} \cdot C_{p_{gas}} @ T_0 \cdot T_{adiabatic}}{A_{heat\ exchange}} \quad (\text{eq.4})$$

Various temperatures are computed as follows:

$$T_{adiabatic} = T_0 \cdot \left(\frac{P_{peak}}{P_0} \right)^{\frac{\gamma-1}{\gamma}} \quad (\text{eq.5})$$

γ for typical gases/vapours used in contact with hydrazine are $\gamma_{\text{He}} = 1.667$, $\gamma_{\text{N}_2} = 1.40$ or $\gamma_{\text{N}_2\text{H}_4(\text{vapour})} = 1.20$ (and specifically assessed within this paper).

$A_{\text{heat exchange}}$ for a cylindrical pipe would correspond to:

$$A_{\text{heat exchange}} = \pi \cdot D \cdot L_{\text{peak}} + \frac{\pi \cdot D^2}{4} \quad (\text{eq.6})$$

$$L_{\text{peak}} = \frac{m_{\text{gas}} \cdot \left(\frac{1000 \cdot R}{MW_{\text{gas}}} \right) \cdot T_{\text{adiabatic}}}{P_{\text{peak}} \cdot \left(\frac{\pi \cdot D^2}{4} \right)} \quad (\text{eq.7})$$

No gas absorption to the liquid or leak is assumed (e.g. m_{gas} is constant).

VALIDATION TEST DATA

Based on the previous section, the following data has been used for the assessment:

Test data	Parameter	Test setup	Test points	Ref.
[B&B]	Push pressure	WSTF mod.	6	[2]
[B&B]	Cavity pressure	WSTF	14	[2]
[B&B]	Length	WSTF	7	[2]
[Benz]	Length	WSTF	8	[1]
ERNO	Cavity pressure	Flight-like	9	[3]
ONERA	Cavity pressure	Own	2	[4]
TOTAL			46	

Table 2. Validation test data

Additional data has been used to calibrate the correction factors:

Test data	Parameter	Test setup	Test points	Ref.
Other data	Push gas	WSTF	2	[1]
Other data	Cavity gas	WSTF	2	[1]
Other data	Catalytic effect	U-tube	11	[5]
Other data	Diameter	WSTF	3	[1]
TOTAL			18	

Table 3. Calibration test data

CALCULATION OF CORRECTION FACTORS

CALCULATION OF C_M

Briles ([5]) identified a change on hydrazine thermal runaway point when the construction material of the experiment was modified. Three groups of materials were identified (in order of compatibility):

- Group 1. SS304, SS316L, SS347, SS321, Hastelloy-X & Haynes 25.
- Group 2. Inconel-X & 17-7PH.
- Group 3. Aluminium alloys Al2014-T6 & Al6061-T6.

Catalytic effects for Titanium are available in ([7]). This data is corrected for comparison purposes with the classification from above. This resulted to be similar to Group 1. For all materials, this is calculated as follows:

$$C_M = \frac{E_{\text{reference}}}{E_{\text{material}} - R \cdot T_0 \cdot \ln\left(\frac{k_{0,\text{reference}}}{k_{0,\text{material}}}\right)} \cdot \frac{T_0}{300} \quad (\text{eq.8})$$

Table 4 provides relevant coefficients for different typical construction materials

	K_0 [mole/(s·m ²)]	E [J/mole]
SS304	1.58E+06	99631
Inconel X	1.43E+10	112820
17-7 PH	1.43E+10	112820
Al 2014-T6	4.28E+09	103845
Al 6061-T6	2.22E+04	72489
SS316L	8.29E+06	104729
SS347	1.81E+03	78807
SS321	5.03E+05	96110
Hastelloy-X	1.58E+06	99631
Haynes 25	1.58E+06	99631
Ti-6Al-4V	7.54E+05	95000
Ti-3Al-2.5V	7.54E+05	95000

Note: Data obtained from [10],[7] and corrected to test data from [5]

Table 4. Catalytic effect coefficients for typical construction materials

When the test has used SS304L as construction material but at a different temperature than 300K, eq. 8 also applies.

CALCULATION OF C_D

Test data confirms that larger diameters increases the risk of hydrazine detonation. Validation is performed for diameters ranging between $\frac{1}{4}$ " and $\frac{1}{2}$ " (i.e.[1]). The proposed equation also confirms this trend and C_D corrects it to match them with empirical results. This is calculated as follows:

$$C_D = -123.67 \cdot D + 2.358 \quad (\text{eq.9})$$

CALCULATION OF C_G

Available data ([5]) suggests that only differences on hydrazine reactivity were found when the propellant contamination were beyond the monopropellant grade specification (e.g. $H_2O > 1\%$, aniline $> 0.5\%$). Test data comparing the chemical compatibility of materials using different grades is rather limited and only tested for long term compatibility at (quasi) ambient conditions. It is generally acknowledged that High Purity grades are more compatible than monopropellant grades. Therefore, although evidence on the effect of adiabatic decomposition when changing the propellant grade is missing, a significant change of performance is deemed unlikely and therefore a $C_G \sim 1$ is suggested when calculating the detonation factor.

CALCULATION OF C_{CG}

When using a cavity gas different than the reference one, the liquid front compresses the gas and local temperature build-up may change, which may induce a significant effect on the hydrazine detonation. The correction factor has been validated with Nitrogen and Helium only due to data availability (i.e. two test points only). For Helium, it is calculated as follows:

$$C_{CG,He} = \frac{\left(\frac{P_{peak}}{P_0}\right)^{\frac{\gamma_{He}-\gamma_{N_2}}{\gamma_{He}\gamma_{N_2}}}}{0.2364 \cdot \left(\frac{P_{peak}}{P_0}\right)^{\frac{\gamma_{He}-\gamma_{N_2}}{\gamma_{He}\gamma_{N_2}} + 0.7636}} \quad (\text{eq. 10})$$

On some test cases from Hutchinson ([3]), hydrazine vapour was used as cavity gas. No detonation data is available for these cases, a value of $C_{CG} = 1$ was used.

CALCULATION OF C_{PG}

One rare test was performed with the cavity filled in nitrogen and using two different push gases: Nitrogen and Helium. The test case using Helium was a more effective push gas and a correction factor was derived accordingly.

$$C_{PG,He} = 1.759$$

DISCUSSION OF RESULTS

Based on the methodology shown above, a total of 46 test cases were evaluated. These test cases were obtained from four different sources and four different test setups. In addition, additional 18 cases

were used to correlate the correction factors shown above.

After the review of the results obtained using the proposed methodology, a trend could be seen: the higher the detonation factor, the higher the risk of detonation. Three regions could be identified (see Figure 4):

- A first region where no hydrazine decomposition could be detected (e.g. similar results as per fluid simulant or no local temperature increase was detected)
- A second region where partial hydrazine decomposition could be detected but did not result in a pipe burst or thermal runaway
- A third region where all test cases resulted in a pipe burst or pipe explosions in several locations which suggest hydrazine became unstable and detonated.

A line could be drawn between the first and second region. This was found to be around 120000 J/m^2 (this would correspond to the point where divergence between water and monopropellant grade hydrazine is found in Figure 1).

As hydrazine decomposition was noticed, the calculated detonation factor was gradually increasing. When the detonation factor exceeded 250000 J/m^2 a transition zone between partial hydrazine decomposition and pipe burst or thermal runaway was detected. Finally when the detonation factor was exceeding 300000 J/m^2 , major hydrazine decomposition/hydrazine detonation was found on all cases.

One single test was performed under vacuum conditions in the gas cavity (e.g. 5 Pa). Although a very large hydrodynamic surge pressure (i.e. $> 1300 \text{ bar}$) was observed, hydrazine showed very similar results with water (which suggests no detonation). Indeed, the computed detonation factor suggests a low risk of hydrazine detonation as the capacity of the cavity gas to store heat is very limited. In this respect, the results could infer to favour pressure transients (e.g. priming) under vacuum conditions. However, although the risk of hydrazine detonation is reduced, a second problematic is introduced by an

increased hydraulic surge pressure in the line which may compromise the structural integrity of the system.

GUIDELINES WHEN EVALUATING HYDRAZINE ADIABATIC DETONATION.

It is widely accepted that detonation of hydrazine is a concern in vapour phase. Indeed Liquid hydrazine is not rated as an explosive under UN Guidelines for Dangerous Goods ([8]). Therefore, at ambient temperature, hydrazine waterhammer in liquid phase (or even small gas voids) at ambient conditions does not induce detonation. Indeed, Rathgeber ([9]) showed results on hammered hydrazine with Helium bubbles up to 1.5% (v/v) using an explosive charge without inducing detonation.

All cases tested ([1],[2],[3]) which resulted in detonation had a rather large gas/vapour cavity which had been compressed by the liquid front.

SAFETY FACTORS

No standardised safety factor policy exists for the assessment of hydrazine detonability risk. In this chapter a safety factor is proposed based upon the uncertainty found during the validation phase.

All 46 test cases were evaluated for detonation using the same methodology. Based on the results found, three risk areas were defined (see above). When the calculated detonation factor fell outside its region, an error was accounted (i.e. relative error with respect to the threshold limit set for each risk area, see Figure 4). Otherwise no error was accounted.

When using this logic, a total of four cases (out of 46) fell outside its correspondent box with an average error of 7% between the first and second region of risk (between no hydrazine decomposition and partial hydrazine decomposition) and 14% between the second and third region of risk (partial hydrazine decomposition to hydrazine detonation). The maximum error found was always below 25% (between the second and the third region only).

Based on the results obtained, a safety factor of 2 in the threshold limit value (i.e. 120000 J/m²) is deemed sufficient to avoid the risk of hydrazine detonation.

Therefore a detonation factor of 60000 J/m² or less should not incur in hydrazine detonation.

SUMMARY AND CONCLUSIONS

For future assessments on hydrazine detonability, a test campaign on a flight representative system is recommended. A test campaign performed with a fluid simulant (i.e. demineralised water) followed by an assessment for the risk of hydrazine detonability could be sufficient.

Several approaches to assess hydrazine detonability from hydrazine simulant hydraulic data can be proposed as long as adequate validation is demonstrated. The present paper proposes one possible approach to assess this risk.

Should a test campaign with real hydrazine be a preferred option, the present paper recommends to run the same test with hydrazine and water in order to detect any partial hydrazine decomposition.

Conclusions on the present paper with regards to the validity of a hydrazine detonability assessment based on simulation tools are based on simulation campaigns performed with EcosimPro. No attempts to validate other numerical tools against priming have been performed internally within ESA-ESTEC.

EcosimPro shows to either correctly or overestimate hydraulic peak pressures for simple pipe manifolds. As a result, an assessment on hydrazine detonability based on an EcosimPro input would provide conservative conclusions.

On the other hand for complex pipe manifolds, preliminary steps which have been performed to validate the EcosimPro tool for priming simulations. Further development and validation work is still required on EcosimPro models to adequately capture hydraulic pressure peaks.

This paper defines a parameter (i.e. Detonation factor) which has been first calibrated and then correlated with the risk of hydrazine detonation. The final goal of the Detonation factor is to define a pass/fail criteria to avoid hydrazine detonation. This has been set at 60000 J/m².

The detonation factor has been validated against 46 test cases. These test results have been generated with four different test setups (see Table 5 for more details).

The detonation factor would still require further validation as experimental data under some conditions is still missing or just limited (e.g. more pipe diameters, more data points for hydrazine discharge under vacuum conditions, etc).

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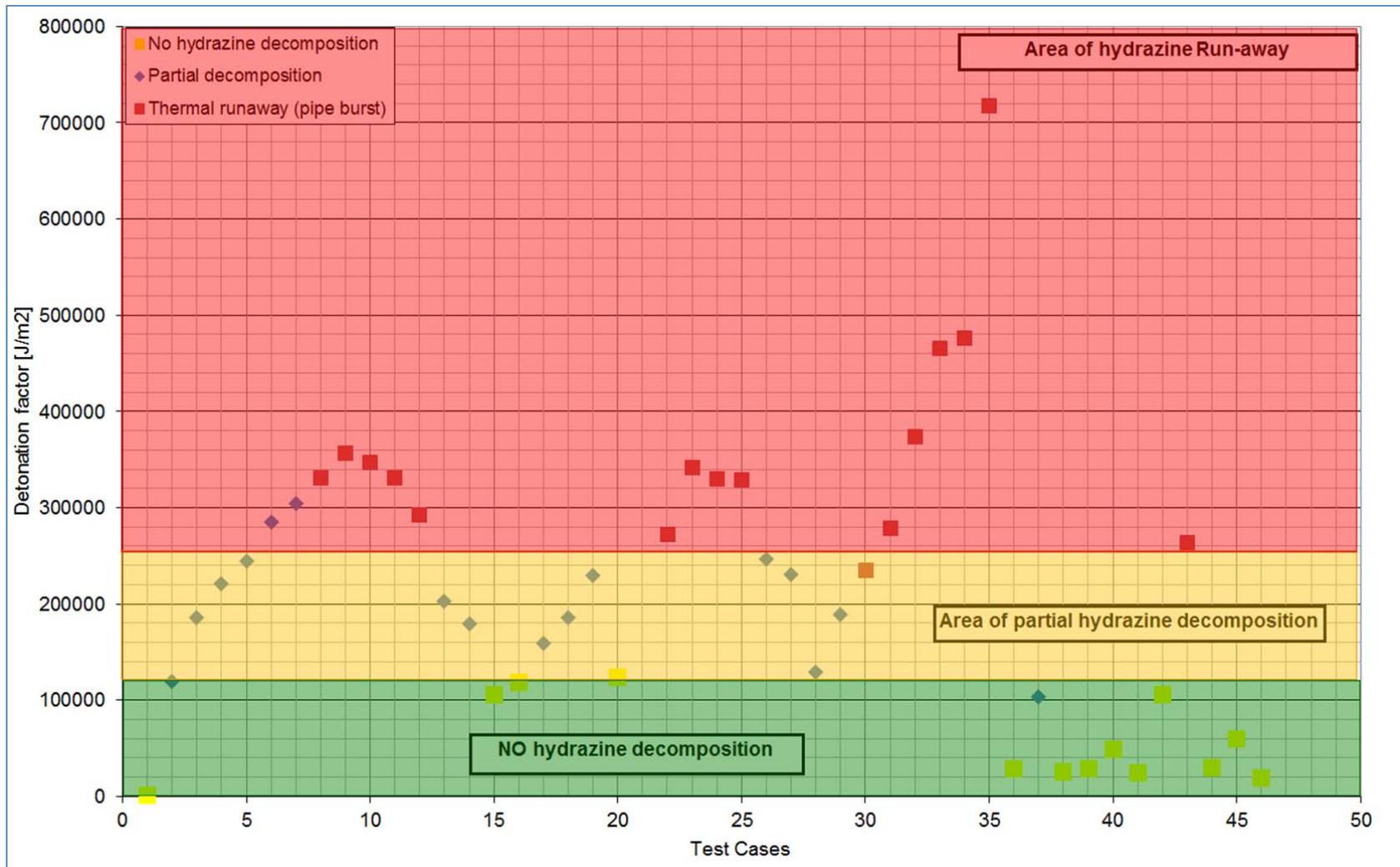


Figure 4. Summary of the test results obtained

Test Case	Test Setup	Liquid Cavity				Gas Cavity					reference
		P [bar]	T[K]	L [m]	D[inch]	Gas	P [kPa]	T[K]	L [m]	D[inch]	
1	WSTF	21	300	0.203	½"	N ₂	0.005	300	0.381	½"	[2]
2	WSTF	21	300	0.203	½"	N ₂	7	300	0.381	½"	[2]
3	WSTF	21	300	0.203	½"	N ₂	14	300	0.381	½"	[2]
4	WSTF	21	300	0.203	½"	N ₂	21	300	0.381	½"	[2]
5	WSTF	21	300	0.203	½"	N ₂	28	300	0.381	½"	[2]
6	WSTF	21	300	0.203	½"	N ₂	41	300	0.381	½"	[2]
7	WSTF	21	300	0.203	½"	N ₂	55	300	0.381	½"	[2]
8	WSTF	21	300	0.203	½"	N ₂	69	300	0.381	½"	[2]
9	WSTF	21	300	0.203	½"	N ₂	85.5	300	0.381	½"	[2]
10	WSTF	21	300	0.203	½"	N ₂	99	300	0.381	½"	[2]
11	WSTF	21	300	0.203	½"	N ₂	113	300	0.381	½"	[2]
12	WSTF	21	300	0.203	½"	N ₂	127	300	0.381	½"	[2]
13	WSTF	21	300	0.203	½"	N ₂	134	300	0.381	½"	[2]
14	WSTF	21	300	0.203	½"	N ₂	141	300	0.381	½"	[2]
15	WSTF modified	15	300	0.203	½"	N ₂	85.5	300	0.381	½"	[2]
16	WSTF modified	17	300	0.203	½"	N ₂	85.5	300	0.381	½"	[2]
17	WSTF modified	21	300	0.203	½"	N ₂	85.5	300	0.381	½"	[2]
18	WSTF modified	35	300	0.203	½"	N ₂	85.5	300	0.381	½"	[2]
19	WSTF modified	69	300	0.203	½"	N ₂	85.5	300	0.381	½"	[2]
20	WSTF modified	18	300	0.203	½"	N ₂	85.5	300	0.381	½"	[2]
21	WSTF	21	300	0.203	½"	N ₂	85.5	300	0.127	½"	[2]
22	WSTF	21	300	0.203	½"	N ₂	85.5	300	0.254	½"	[2]
23	WSTF	21	300	0.203	½"	N ₂	85.5	300	0.508	½"	[2]
24	WSTF	21	300	0.203	½"	N ₂	85.5	300	0.635	½"	[2]
25	WSTF	21	300	0.203	½"	N ₂	85.5	300	0.762	½"	[2]
26	WSTF	21	300	0.203	½"	N ₂	85.5	300	0.889	½"	[2]
27	WSTF	21	300	0.203	½"	N ₂	85.5	300	1.016	½"	[2]
28	WSTF	139	421	0.203	½"	N ₂	85.5	421	0.051	½"	[1]
29	WSTF	139	298	0.203	½"	N ₂	85.5	298	0.102	½"	[1]
30	WSTF	139	366	0.203	½"	N ₂	85.5	366	0.102	½"	[1]
31	WSTF	139	298	0.203	½"	N ₂	85.5	298	0.152	½"	[1]
32	WSTF	139	298	0.203	½"	N ₂	85.5	298	0.203	½"	[1]
33	WSTF	139	366	0.203	½"	N ₂	85.5	366	0.203	½"	[1]
34	WSTF	139	298	0.203	½"	N ₂	85.5	298	0.254	½"	[1]
35	WSTF	139	298	0.203	½"	N ₂	85.5	298	0.381	½"	[1]
36	ONERA	21	293	Tank	¼"	N ₂	500	293	2.00	¼"	[4]
37	ONERA	21	293	Tank	¼"	N ₂	100	293	2.00	¼"	[4]
38	ISPM	26	313	Tank	¼"	N ₂	100	313	2.045	¼"	[3]
39	ISPM	26	313	Tank	¼"	25% N ₂ 75% N ₂ H ₄	100	313	2.045	¼"	[3]
40	ISPM	26	313	Tank	¼"	10% N ₂ 90% N ₂ H ₄	100	313	2.045	¼"	[3]
41	ISPM	26	313	Tank	¼"	25% N ₂ 75% N ₂ H ₄	400	313	2.045	¼"	[3]
42	ISPM	26	313	Tank	¼"	98% N ₂ H ₄ (v) 2% N ₂ H ₄	4.5	313	2.045	¼"	[3]
43	ISPM	30	351	Tank	¼"	98% N ₂ H ₄ (v) 2% N ₂ H ₄	43.8	363	2.045	¼"	[3]
44	ISPM	25.8	343	Tank	¼"	25% N ₂ 75% N ₂ H ₄	200	343	2.045	¼"	[3]
45	ISPM	25.8	343	Tank	¼"	5% N ₂ 95% N ₂ H ₄	200	343	2.045	¼"	[3]
46	ISPM	25.8	343	Tank	¼"	99% N ₂ H ₄ 1% N ₂ H ₄ (v)	19.3	343	2.045	¼"	[3]

Table 5. Summary of main test conditions