Impact fragmentation of polymetallic nodules under deep ocean pressure conditions

J.M. van Wijk\textsuperscript{a,b}, S. Haalboom\textsuperscript{b}, E. de Hoog\textsuperscript{a}, H. de Stigter\textsuperscript{b}, M.G. Smit\textsuperscript{b}

\textsuperscript{a} Royal IHC, Smitweg 6, 2963 AW Kinderdijk, the Netherlands
\textsuperscript{b} NIOZ – Royal Netherlands Institute for Sea Research, ’t Horntje, Texel, the Netherlands

1. Introduction

The mining of poly metallic nodules from the seafloor comprises excavation or pickup, vertical transport to the sea surface and the processing and shipping of the material afterward. Polymetallic nodules from the deep-sea bed of the Clarion Clipperton Zone (CCZ), a prospective mining area, are typically abundant at depths of around 5000 m under ambient pressures of 500 bar. The particle size distribution of the mixture leaving the Vertical Transport System (VTS) is a key design parameter for the ore processing equipment, hence it is of importance to know how nodules will be degraded or fragmented under different conditions of ambient pressure occurring during upward transport in the VTS while passing through a series of centrifugal pumps supporting the flow in the VTS. Up to date, quantification of nodule degradation by predictive models is impossible due to the unavailability of data. In this paper, results of experiments performed with CCZ nodules passing through a centrifugal pump under ambient pressures between 5 and 500 bar at different pump speeds are reported. The fragmentation of the nodules into smaller size classes was determined and complementary experiments on nodule fragmentation under atmospheric pressure conditions at different impact velocities are reported.
the PSD of nodules after circulation through a flowloop with centrifugal pump, matching the residence time in a then envisaged commercial system. The results show that 10% of the nodule fragments is in the class $d < 0.11 \text{ mm}$. Due to their geological nature, polymetallic nodules can be seen as heterogeneous agglomerates of mineral particles. The mechanical properties of polymetallic nodules are known to some extent (Dreiseitl, 2017), but thus far they have not been related to nodule degradation. Breakage of small particles (sub-millimeter scale) is studied in the research field of powder technology. Although powders are very small compared to polymetallic nodules, the methods and models used in this research field can provide more insight into our field. Pitchumani et al. (2003, 2004) developed multiple test setups to investigate agglomerate attrition, i.e. normal impacts (with a flat plate in this case) with low forces. Reynolds et al. (2005) give an overview of particle breakage research, of which the single particle impact tests and the associated statistics for analysis stand out as a useful method for a more detailed analysis of fracturing mechanisms of polymetallic nodules. Particle strength is identified as a very important parameter characterizing the fracturing process, but it should be noted that in the case of multiphase flows through centrifugal pumps particle properties cannot be seen independently from the flow characteristics and both particle properties (e.g. size, shape, strength) and the flow and fluid (e.g. velocities, direction, wetness) play a role.

Recent work by Zenhorst (2016) focused on degradation of natural, water saturated polymetallic nodules (the largest having a diameter of about $d = 67 \text{ mm}$) under atmospheric conditions. He used a test circuit with a $D_i = 300 \text{ mm}$ centrifugal pump with only ten meters of steel pipeline with two 90° bends (pumping nodules from one basin to another). The setup was operated at $n_p = 450 \text{ rpm}$ resulting in a fluid velocity of $v_f \approx 4 \text{ m/s}$ in the suction and discharge lines. Associated nodule velocities will be smaller. Initially and after ten passages, the PSD of the batch was determined. The setup is representative for real transport conditions in terms of nodule velocity and pump dimensions, but due to the short pipeline length the pump rotational speed is relatively low. Furthermore, degradation of particles under atmospheric conditions could be different from degradation under deep sea conditions. Zenhorst (2016) observed that particle sizes asymptotically approached a distinct minimum particle size, i.e. the nodules tended not to get smaller than a certain lower level.

In Van Wijk (2017) an engineering model for the degradation (impact fragmentation) of polymetallic nodules has been proposed based on the relation suggested by Wilson and Addie (1997) and estimated typical degradation rates for polymetallic nodules under atmospheric conditions based on the Zenhorst data. Van Wijk (2017) modelled degradation as exponential decay of particle size while Pitchumani et al. (2004) models exponential decay of the mass fraction of a species remaining in its original size class. A third approach is proposed by Chapelle et al. (2004b,a). They study particle degradation (combined impact fracturing and particle attrition) during pneumatic conveying. They use species redistribution, i.e. after a single impact $x\%$ of particles from a specific size class remain in their original class while $y\%$ moves into the next (in descending order), $z\%$ moves into the class thereafter, etc. Each species thus will be redistributed over itself and all available smaller size classes.

Previous studies on rock mechanics have indicated that under high ambient pressures as occurring in the deep sea, fracturing of rocks requires more energy (Helmons, 2017). This may have implications for the harvesting process of polymetallic nodules from the deep-sea bed of the Clarion Clipperton Zone, where nodules are typically abundant at depths of around 5000 m under ambient pressures of 500 bar. It is of particular importance to know how nodules will be degraded under different conditions of ambient pressure occurring during upward transport in the VTS, while colliding with other nodules and while passing through a series of centrifugal pumps supporting the flow in the VTS. The degree of nodule degradation in the VTS is an important parameter for estimating the volume of recoverable ore delivered at the surface, relative to the volume of fine-grained nodule grit smaller than $8 \mu m$ which technically cannot be recovered and eventually must be discharged. Concerning the discharge of fines, their size distribution is an important parameter for modelling the dispersion in the marine environment and assessing impact on marine biota.

With respect to the degradation of polymetallic nodules, essential data is missing. No data is known on the degradation of polymetallic nodules of realistic sizes under typical operational conditions, and especially the influence of high ambient pressure on the degradation process is unknown. In order to gather the essential data, a test setup was constructed in the pressure test tank at the NIOZ. The experiments focus on impact fracturing of the nodules in a centrifugal pump. Complementary tests have been conducted at IHC MTI in which the impact fragmentation process itself was studied in more detail.

2. Materials and methods

2.1. Experiments at high ambient pressure conditions

The test setup at the NIOZ was constructed to accommodate the largest nodules that can reasonably be expected during normal VTS operation, e.g. $d/D_i \approx 3/5$. The test setup is depicted in Fig. 1. It consists of a nodule carousel (1) in which up to 30 nodules can be loaded to be individually launched into the suction tube (2). The nodules are vertically accelerated towards the suction inlet of the pump (3). The pump is driven by an oil-filled pressure compensated electromotor (5). Just before entering the pump, the nodule velocity $v_i$ is measured using two pairs of non-intrusive electromagnetic probes integrated in the tube, that produce a signal upon passing of the nodule. The average nodule velocity is calculated from the time difference between the two signals and the distance between the sensors. After passage of the pump, the
nodule enters the hydrocyclone (4) where the fine grit and coarser fragments are separated to enable detailed analysis of the particle size distributions.

For the nodule degradation experiment, 45 kg of dry polymetallic nodules retrieved from the Belgian contract area in the CCZ were used, followed by experiments with wet nodules from the UK contract area in the CCZ. The nodules were mostly too large to fit in the carousel and ducts of the test setup, therefore nodule fragments with a diameter of
were selected for the tests. In contrast to the rounded appearance of intact nodules, these fragments were mostly of irregular and angular shape. The fragments have been formed due to disintegration of intact nodules along the internal weakest parts. The fragments themselves could therefore be relatively strong compared to the original intact nodules.

Prior to the experiments, nodules were immersed for two months in fresh water at 5 °C in darkness in order to completely saturate them with water. Salinity was assumed to be of no importance for the mechanical strength of the nodules. Before use, the nodules were pressure-washed with water to remove adhering fine-grained nodule grit and remains of sediment. After draining off adhering water with a sponge the nodules were individually weighed wet, and subsequently immersed in water again until further use. Considering that the drying of the Belgian nodules could have affected their mechanical strength, a second batch of nodules was obtained, which had been retrieved from the UK contract area in the CCZ and which had been permanently kept immersed in water. This second batch included numerous intact nodules small enough to fit in the test setup.

In the tests, nodules were passed through the setup applying different pump velocities (750, 1200 and 1800 rpm respectively) and ambient pressures of 5, 95, 189, 283, 378 and 500 bar, as indicated in Table 1. For each test run, the hyperbaric tank was filled with clean water of about 15 °C. After completing a test run, nodules and nodule grit captured in the collecting chamber mounted under the hydrocyclone were recovered. Nodule grit that had escaped from the open top of the hydrocyclone was recovered by pumping the full content of the tank over a 63 μm sieve and adding the retained material to the grit captured in the collecting chamber. Nodules and nodule grit recovered after each test run were wet-sieved over a series of sieves with logarithmically increasing mesh size of 0.063 mm, 0.125 mm, 0.250 mm, 0.500 mm, 1.000 mm, 2.000 mm, 4.000 mm, 8.000 mm, 16.00 mm and 32.00 mm. The retained fractions were freeze-dried and weighed.

From the total volume of water used for sieving and retrieved from the hyperbaric tank two homogeneous 2 L samples were retained for analysis of the particle fraction d < 63 μm which had passed through the smallest sieve mesh. One 2 L sample was filtered over 0.4 μm polycarbonate filter and the retained material weighed after freeze-drying. The other 2 L sample was left for 3–5 weeks in order to let particles settle out. After carefully draining off the overlying water the particle size distribution of the condensed suspension was measured with a Beckmann-Coulter LS230 laser particle sizer, using the smallest-volume measuring cuvette. Sodium pyrophosphate solution was added as dispersant, and multiple measuring rounds were performed until a stable measurement cuvette. Sodium pyrophosphate solution was added as dispersant, and multiple measuring rounds were performed until a stable size distribution of the particle size distribution was found. Size classes as reported by the laser particle sizer were rearranged into size classes with logarithmically increasing boundaries of 1, 2, 4, 8, 16, 32 and 64 μm, continuous with the size classes applied for the sieved fractions. In the end, weight percentages of all dry fractions were calculated relative to the summed weight of all fractions together.

Next to single runs carried out under one particular combination of pump speed and pressure, two series of tests were carried out simulating the passage of nodules through the full series of pumps of the VTS positioned at different water depths. While running the pump at different velocities, respectively, nodules and nodule grit were passed multiple times through the pump, consecutively at 500, 378, 283, 189, 95 and 5 bar. In order to avoid obstruction of the carousel by fine grit entering between moving parts, material with d < 2 mm was sieved out after each run and only nodules and grit with d > 2 mm placed back in the carousel. Only at the end of a complete series of tests the fine-grained material contained in the pressure tank was retrieved and treated as previously described.

It should be noted here that the fine-grained material retrieved from the water in the hyperbaric tank contained abundant chips of blue paint abraded from the interior of the hydrocyclone. The relatively light paint chips could be effectively separated from the denser nodule grit by flotation on water. The presence of paint chips, however, provides evidence of abrasion occurring within the hydrocyclone, adding fine-grained material to the fractions produced in the pump. In order to verify what extend pure impact fragmentation is associated with the production of very fine material, additional experiments were conducted at IHC MTI. The additional tests will be discussed in the next section.

2.2. Additional experiments at atmospheric pressure

In the additional tests, water saturated Belgian CCZ nodules were dropped from a predetermined height in air, landing on a stiff flat steel plate in an open box with a few millimeters of water at the bottom. The nodules were fully intact while at NIOZ the nodules were sized to the required size. A top view of the test setup is shown in Fig. 2. The water was applied in order to have a similar velocity reduction as would be the case during submerged collision, since in both cases water would be squeezed between the nodule and the plate. In total ≈ 19 kg of water-saturated nodules were dropped in the size classes 64–128 mm (63%), 32–64 mm (29%) and 16–32 mm (8%). After each test, the nodules were collected, weighed and sieved in order to determine the particle size distributions. Three different heights were used in order to arrive at velocities of v1 = 4 m/s, v2 = 6 m/s and v3 = 8 m/s. The v3 = 4 m/s test comprised three consecutive impacts of the same batch of nodules, while the tests at v1 = 6 m/s and v2 = 8 m/s were single impact events. The actual drop of a nodule was recorded by a high speed camera, providing insight in the breaking mechanism of the nodules. A video still is shown in Fig. 3.

3. Theory

3.1. Susceptibility to impact fragmentation

Consider a single, spherical nodule that is followed through a centrifugal pump. It is assumed that the nodule enters the pump with the mixture bulk velocity, and its path during entry is aligned with the axis of rotation of the impeller. The interaction between the nodule and the impeller follows three dominant stages. The first is the possible collision between the nodule and the impeller nose at the inlet, after which the

| Ambient pressure p [bar] | Nodule velocity v3 [m/s] | Pump speed [m/min] | Experiment |
|--------------------------|--------------------------|-------------------|------------|
| 5                        | 1.86                     | 750               | 4          |
| 5                        | 2.82                     | 1200              | 6          |
| 5                        | 4.13                     | 1800              | 2          |
| 5                        | 1.81                     | 750               | 25 UK      |
| 5                        | 2.85                     | 1200              | 27 UK      |
| 5                        | 4.33                     | 1800              | 26 UK      |
| 95                       | 1.82                     | 750               | 10         |
| 95                       | 4.16                     | 1800              | 11         |
| 189                      | 1.85                     | 750               | 12         |
| 189                      | 4.06                     | 1800              | 13         |
| 283                      | 1.78                     | 750               | 9          |
| 283                      | 2.80                     | 1200              | 7          |
| 283                      | 4.08                     | 1800              | 8          |
| 379                      | 1.87                     | 750               | 14         |
| 379                      | 4.10                     | 1800              | 15         |
| 500                      | 1.92                     | 750               | 23         |
| 500                      | 2.84                     | 1200              | 28 UK      |
| 500                      | 1.83                     | 750               | 3          |
| 500                      | 2.82                     | 1200              | 5          |
| 500 – 379 – 283 – 189 – 95 – 5 | 1.87                  | 750               | 16         |
| 500 – 379 – 283 – 189 – 95 – 5 | 4.24                  | 1800              | 17         |
nodule is redirected 90° into the impeller. When the nodule moves between the blades there is the possible impact with the impeller blades, resulting in a second collision. After leaving the impeller there is a second 90° redirection of the nodule towards the pump outlet.

A time-scale analysis can be used to judge to what extent a nodule is following the dominant flow direction, and thus to judge on the susceptibility of collision. The Stokes number expresses the ratio between the typical particle reaction time and the time-scale of its environment:

$$St = \frac{t_p}{t_f}$$  \hspace{1cm} (1)

With $St$ the Stokes number, $t_p$ the particle reaction time and $t_f$ the typical timescale of its environment, e.g. the flow field in which the particle moves. $t_f$ varies with the region of interest as detailed below. When $St \ll 1$, this implies that the particles are not significantly influenced by the external flow field, while $St \gg 1$ implies that the particles are directly influenced by changes in the external flow field. $St$ thus is an indicator of relevant processes with respect to particle degradation.

The nodules have different reaction times to fluctuations in the flow, based on their diameter and density. The nodule reaction time is defined as 63% of the time required to obtain its terminal settling velocity, which can be derived from the equation of motion of a solid sphere submerged in a fluid (neglecting added mass):

$$\frac{\partial w}{\partial t} = -\frac{\rho_f}{\rho_p} \cdot g - \frac{1}{2} \cdot C_D \cdot A_p \cdot \rho_f \cdot w^2$$  \hspace{1cm} (2)

Eq. (2) has an analytical solution:

$$w(t) = \sqrt{\frac{2 \cdot (\rho_f - \rho_p) \cdot V_p \cdot g}{\rho_f \cdot A_p \cdot C_D}} \cdot \frac{\tanh \left( \frac{(\rho_f - \rho_p) \cdot A_p \cdot C_D \cdot g}{2 \cdot (1/2 \rho_f)^2} \cdot V_p \cdot t \right)}{\left( \frac{\rho_f - \rho_p}{1/2 \rho_f} \cdot A_p \cdot C_D \cdot g \right)}$$  \hspace{1cm} (3)

Eq. (3) is used to find $t_p$ by solving $w(t_p) = 0.63 \cdot w_0$, with $w_0$ being the terminal settling velocity of the particle. The relevant timescales of the flowfield depend on the (bulk) nodule velocity $v_i$ and the dimensions of the sections of interest. These are the pump width $W$, the suction diameter $D_s$ and the impeller diameter $D_o$.

The first area of interest is the inlet zone, where the flow timescale is defined as:

$$t_f = \frac{W}{v_i}$$  \hspace{1cm} (4)

The second area of interest is related to the impeller blade passage, which gives a timescale:

$$t_f = \frac{60}{N_b \cdot n_p}$$  \hspace{1cm} (5)

With $N_b$ the number of blades and $n_p$ the rotational speed of the pump in rpm. The last timescale of interest is related to the time required for a nodule to flow through the impeller in radial direction:

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**Fig. 2.** Top view of the flat plate of the experiments at atmospheric conditions. Nodules were dropped from a fixed height in order to collide with the plate at velocities of $v_4 = 4 \text{ m/s}, \ v_6 = 6 \text{ m/s}$ and $v_8 = 8 \text{ m/s}$. After each impact, debris were collected, weighed and sieved.
With $v_f$ being the average fluid velocity at the inlet of the pump. Substitution of $t_p$ and $t_f$ in Eq. (1) for the cases of Eqs. (4)–(6) for different values of particle diameter $d$ and pump speeds $n_p$ can be used to assess the impact fracturing susceptibility of particles.

Comparing the particle reaction time to the inlet zone timescale of Eq. (4), using the geometry of the centrifugal pump used in this paper, shows that $St \ll 1$ for all particles in the class $16 < d \leqslant 32$ mm even for the smallest nodule velocities found in the experiments. This means that upon entering the pump, nodules will decelerate and eventually collide with the impeller nose. The nodule will typically hit the nose with a velocity of $v \leq v_s$, depending on the nodule deceleration near the nose. A detailed analysis around the nose is required to get a more precise indication. The order of magnitude is expected to be dominated by $v_s$. It is interesting to look at the lower asymptote in particle size to find the particle size at which no collision in the inlet zone will occur. Solving Eq. (4) for $St = 1$, now using $v_s = 4.5$ m/s (which is about the upper limit of velocity found in the experiments) it is found that particles with $d = 0.6$ mm will not collide at the inlet zone.

The ratio between particle reaction time and the impeller speed timescale of Eq. (4) shows $St > 1$ for all particle diameters in the largest size class, which implies that when a particle is in the vicinity of an impeller blade, it will certainly get hit. The collision will be oblique with the dominant velocity dictated by the impeller speed. A more detailed analysis is required to get a more precise indication of the relative velocity at collision, however the order of magnitude is expected to resemble the impeller velocity. For this process, the lower

$$t_r = \frac{D_p(D_r + D_f)}{D_f^2 v_f}$$

(6)
particle diameter asymptote found at \( St = 1 \) is \( d = 0.29 \) mm.

Whether a particle will be hit by the impeller blades (on average) can be analysed by comparing the timescale of the impeller, Eq. (5), and the typical residence time of a particle in the channel between impeller blades, Eq. (6). It now proves that \( St \gg 1 \) for all pump speeds used in the experiments, assuming that all particles move approximately with the largest velocity \( v_f \) found in the experiments. This means that the collision with an impeller blade has a large influence on the impact fracturing of the nodules, and from the pump related parameters, the pump speed is expected to be the dominant one.

3.2. Modelling impact fragmentation

In Van Wijk (2017) an engineering model for impact fragmentation of polymetallic nodules has been proposed based on the relation suggested by Wilson and Addie (1997). The idea is that after degradation, a particle is fractured into new particles with sizes smaller than the original particle size, and the model follows the size development of specific (groups of) particles:

\[
\frac{d_i}{d_{i,0}} = \exp(-k_i N)
\] (7)

Here \( d_{i,0} \) is the particle diameter of fraction \( i \) after \( N \) pump passages, \( d_{i,0} \) is the initial particle size of fraction \( i \) and \( k_i \) is the rate of degradation of fraction \( i \). Van Wijk (2017) estimated degradation rates \( k_i \) of the individual fractions by rewriting Eq. (7) as \( k_i = -\log_e d_{i,N}/d_{i,0} \) which was a pragmatic way to assess to total degradation of material after \( N \) impacts provided that the data used for the prediction also was obtained for the same amount of impacts. Proper assessment of the degradation rates require the increment \( \Delta N = 1 \), i.e. \( k_i = -\log_e d_{i,N+1}/d_{i,N} \), so after each impact event the new PSD can be constructed.

Pitchumani et al. (2004) model degradation by looking at the mass fractions in the particle size distribution rather than the actual particle sizes. They calculate the amount of material \( x_i \) that remains in the original size class after an impact event:

\[
\frac{x_{i,N}}{x_{i,0}} = \exp(-k_i N)
\] (8)

where \( x_{i,N} \) is the mass fraction remaining in size class \( i \) after \( N \) impact events, \( x_{i,0} \) is the original mass fraction in size class \( i \) and \( k_i \) is the rate of degradation of the species in class \( i \). Note that \( k_i \) in the models of Van Wijk (2017) and Pitchumani et al. (2004) are not similar since their (experimental) basis is different, and furthermore note that estimation of \( k_i \) in Eq. (8) should also be based on discrete events, i.e. increment \( \Delta N = 1 \).

The method proposed by Chapelle et al. (2004b) revolves around experimental determination of a breakage matrix \( B \), that relates the initial vector of masses per particle size class \( f_i \) (particle size distribution) to the vector of mass fractions of the size classes after an impact event \( f_i \):

\[
B \cdot f_i = f_i
\] (9)

For \( N \) impact events of size class \( i \) this method can be generalized to repeated application of Eq. (9) to each new particle size distribution.

Both models based on mass fractions rather than particle diameter reduction, Eqs. (8) and (9), have the benefit of directly relating to experimentally determined particle size distributions, in which the size classes are the independent parameter and the mass fractions are the measured parameter. The use of these models prevails over Eq. (7). The main difference between Eqs. (8) and (9) is that Eq. (8) looks at mass loss from individual size classes, not taking into account the equal increase in mass in all subsequent smaller size classes, while (9) provides a total view on the particle size distribution by, per definition, relating pre- and post-impact conditions. The latter requires an extensive body of data before it can be fully used since fragments from one size class theoretically could be distributed over all subsequent size classes.

Data on degradation or fragmentation of polymetallic nodules is very scarce, making predictive calculations with the above models very uncertain. The NIOZ experiments primarily focused on the effect of large ambient pressures on nodule degradation and we only studied the degradation of a single size class, allowing only for determination of a few elements in matrix \( B \) in Eq. (9). The IHC MTI experiments comprise repeated impacts of a batch of nodules with particle sizes spanning three size classes, allowing for determination of a few more elements, but still not sufficient for predictive calculations.

The NIOZ data (high ambient pressure) start with all nodules in size class 16 \( \leq d < 32 \) mm, so in the framework of Eq. (8) it follows \( x_{16 \leq d < 32,0} = 1 \). Many of the NIOZ experiments comprise single impact events at different conditions. Substitution of \( N = 1 \) and \( x_{16 \leq d < 32,0} = 1 \) in Eq. (8) directly provides \( k_{16 \leq d < 32} = -\log_e x_{16 \leq d < 32} \).

In this way however, the remainder of the PSD measured at NIOZ is not used in modelling the impact fracturing. The IHC MTI experiments (atmospheric conditions) comprise multiple impacts of the same (batch of) nodules and their fragments, providing the rate of degradation of more, but not all fractions.

In the analysis of degradation, we will use Eq. (8) as a starting point. Full predictive modelling of nodule degradation is not possible (yet) using the above models since they all require a substantial amount of data, which is not available with the current research and in literature. Given the scarcity of data, it would be interesting to investigate a modelling approach that would allow for full PSD predictions only using a limited number of tests. The design of an improved engineering model and its associated standard test that could be conducted on a sample of poly metallic nodules is outside the scope of the current work.

4. Results

4.1. Experiments at high ambient pressures

An overview of the experiments and test conditions is given in Table 1. All experiments are single passage experiments with a batch of nodules, except for experiments 16 and 17 which comprise successive passages of the same batch of material through the pump at decreasing ambient pressures, mimicking the passage of nodules through the VTS.

Note that in this paragraph both the nodule entry velocity \( v_i \) and the pump speed are used in relation to the presented data. Both are relevant, since the nodule velocity mainly determines fracturing at the inlet zone of the pump while pump speed determines fracturing during impeller collisions.

The main question at the onset of this research was if very high ambient pressure has a significant influence on the degradation rate of polymetallic nodules. Fig. 4 shows the particle size distributions produced at different ambient pressures but similar pump speeds of 750 rpm and 1800 rpm respectively. From this figure it shows that the redistribution of material after impact fracturing is hardly influenced by the ambient pressure. At all pressures at 750 rpm, on average 73% of all nodules remain in the original size class \( 16 \leq d < 32 \) mm and about 18% of the fragments belong to the class \( 8 \leq d < 16 \) mm. From this figure it also shows that the remaining 9% of the material is distributed approximately evenly over all smaller fractions, with a relatively large amount of \( d < 0.063 \) mm material compared to the two size classes just above the smallest. This could be attributed to the effect of the hydrocyclone, where abrasion dominates, and will be further discussed using the IHC MTI experiments.

The results at 1800 rpm show a similar trend, but now far more material has fractured and moved into smaller size classes. On average 46% of the material remained in the largest size class while 27% was degraded to the class \( 8 \leq d < 16 \) mm. The remaining 27% is seen to be distributed evenly over the remaining size classes with \( d < 8 \) mm.

At this point it is interesting to introduce the comparison between nodules with different histories. The Belgian nodules, that had been
dried and subsequently were re-saturated with water, are compared in Fig. 5 with the UK nodules that had remained water-saturated all the time. At 750 rpm the Belgian nodules show more fragmentation than the UK nodules, with 69% of nodules remaining in the original size class compared to 80% for the UK nodules. At 1200 rpm the Belgian nodules show less fragmentation than the UK nodules, with 51% of nodules remaining in the original size class compared to 40% for the UK nodules. At the highest pump speed of 1800 rpm, 30% of the Belgian nodules and 31% of the UK nodules remain in the original size class, while in the subsequent smaller class of $16 < d < 8 \text{ mm}$ 33% of nodule mass is found for the Belgian nodules compared to 45% for UK nodules.

The single passage experiments show hardly any influence of the high ambient pressure conditions, and a large influence of nodule velocity or impeller speed. The sequential experiments in which the same batch of nodules was pumped at decreasing ambient pressure with six stages in total is therfore not expected to be influenced by the changing ambient pressure. Pump speed however does have a large influence on nodule degradation, so for the sequential experiments more degradation is expected at higher pump speeds as well.

Given the observation that mainly the pump speed or nodule velocity is relevant for the impact fracturing process, the next step in the analysis is calculation of the degradation rate $k_i$ for the largest size class at different pump speeds by using Eq. (8). Since all nodules originally were in the $16–32 \text{ mm}$ size class, $k_{6–32 \text{ mm}}$ directly follows from the mass fraction of the nodules left in this class. The result for the NIOZ data is shown in Fig. 6. The trend of the data is positive with increasing pump speed and associated nodule velocities. The ratio between the minimum and maximum at 750 rpm is 2.8 and a ratio of 2 between the minimum and maximum at 1800 rpm was found. In these experiments higher impeller speeds mean both a higher impact velocity with the impeller nose and with the impeller blades, which are in fact two distinct processes. A more detailed study of impact fracturing on the level of individual poly metallic nodules, taking into account forces and stresses, is needed to precisely clarify the failure mechanisms.

Fig. 7 shows the particle size distributions after six pump passages at 750 rpm and 1800 rpm. The consequence of the increased pump speed now is very clear, with only 5% of nodules left in the original size class at 1800 rpm compared with 40% at 750 rpm. The increase in the $63 < d < 0 \text{ µm}$ size class even amounts to 20% at 1800 rpm. Abrasion in the hydrocyclone is expected to have greatly contributed to the fines production since the sequential experiments took much more time than single passage experiments, thereby promoting the abrasion process.

For application of Eq. (8) the PSD should have been measured after each impact in order to analyse the discrete impact events. However, we can calculate an average degradation rate after $N = 6$ passages as $\bar{k}_i = -1/N \log_{10} \left( X_{6–32 \text{ mm}}/X_{6–32 \text{ mm,0}} \right)$. For the 750 rpm sequence it follows $\bar{k}_i = 0.15$ and for the 1800 rpm sequence it follows $\bar{k}_i = 0.50$. Both numbers are just a bit smaller than the lower limits found shown in Fig. 6, being $k_i = 0.18$ for the tests at $p = 95$ bar. This is a significant deviation from the averages of the single passage results.

There is no explanation yet for this phenomenon, but it is expected that this relates to a combination of particle size (smaller particles resulting in less severe collisions with the impeller blades) and changing mechanical properties of the fragments (smaller fragments possibly have less weak fracture planes than the larger fragments due to their
The additional experiments at atmospheric pressure

The additional experiments at atmospheric pressure were conducted at IHC MTI to verify whether pure impact fragmentation is associated with the production of fines, as was found at the high ambient pressure tests at high pump speeds. Fig. 8 shows the original particle size distribution and the resulting distributions after one, two and three repeated impacts with \( v_i = 4 \text{ m/s} \) of a batch of nodules with the plate. The batches were sieved down to 63 μm. The three impact events at \( v_i = 4 \text{ m/s} \) result in 14% of nodules remaining in the 64–128 mm size class, 34% in the 32–64 mm class, 47% of nodules in the 16–32 mm and 3% in the 8–16 mm class. The remaining 2% is distributed over the classes down to \( d = 63 \text{ μm} \). The fraction \( d < 63 \text{ μm} \) is less than 0.01%, which is significantly smaller that the amount of \( d < 63 \text{ μm} \) material found in the NIOZ experiments.

Fig. 9 shows the results of single impact events of a batch of nodules at \( v_i = 4 \text{ m/s}, v_0 = 6 \text{ m/s} \) and \( v_1 = 8 \text{ m/s} \). It is clear that the higher impact velocity is associated with increased fragmentation, similar to what was observed for the NIOZ experiments. After one impact no significant amount of nodules in the \( d < 63 \text{ μm} \) class was found, irrespective of the impact velocity.

Contrary to the NIOZ data, the IHC MTI tests started with nodules in different size classes rather than all nodules from a single class, and the nodules were initially intact rather than sized. The intact nodules could be relatively weak compared to the sized nodules, since the sized nodules are already broken along the weakest internal fracture planes. Size classes smaller than the largest size classes will not only lose material upon fragmentation, but will also be fed with new material from the larger size classes. Both effects play a role when determining the degradation rates with the definition of Eq. (8). The degradation rates of the three largest size classes as found for the single impact experiments under atmospheric conditions are shown in Fig. 10. The degradation rates reflect the net effect of influx and out-flux of material. The smaller size class (16–32 mm) shows negative rates: there is a net accumulation of material in this size class. The rates of the largest size class (128–64 mm) increase upon increasing impact velocity, pointing at an increasing rate of material loss from this class. The size class in between (32–64 mm) shows net accumulation at 4 \( \text{m/s} \) (negative \( k_f \)) and net loss at 8 \( \text{m/s} \) (positive \( k_f \)).

The degradation rates of the 128–64 mm size class per definition only show material loss, which is comparable with the nature of the degradation rates of the NIOZ experiments. This can be seen by the similar positive trend of the data: higher impact velocities result in an increased rate of fragmentation. The absolute value of the degradation rates under atmospheric conditions is significantly larger than the ones found at NIOZ. The velocity scales are not comparable since at NIOZ a centrifugal pump was used and at MTI pure collision with a flat plate was used, and the particle sizes are not comparable either because the largest nodules at MTI were two classes larger than the largest at NIOZ. It is not possible yet to attribute the larger degradation rate found at the atmospheric tests to either a possibly higher impact velocity or to the larger particle size and the particle’s internal structure. However, the order of magnitude of the degradation rates is similar.
pure fragmentation is substantially smaller than found at NIOZ. These experiments furthermore are suitable for studying impact mechanics in more detail, being complementary to the NIOZ experiments. Their value for studying impact mechanics need to be further explored in combination with modelling based on limited data sets.

The experiments at NIOZ mimicked the envisaged transport process which makes use of centrifugal pumps as well. An important objective of the research at NIOZ was to quantify the fraction of fine material (e.g. \( d < 63 \mu m \)) with the requirement to measure even the fractions with \( d < 8 \mu m \). This required the use of a hydrocyclone for separation of different fractions. After the test it was clearly visible by the abraded blue paint, that substantial abrasion took place in the hydrocyclone. Figs. 4 and 5 show that there is more material in the 0–63 \( \mu m \) class than in the 63–125 \( \mu m \) and 125–250 \( \mu m \) classes. The dominance of the smallest size class can only be explained by nodule abrasion, since fragmentation is associated with the larger particles (as shown with the time scale analysis) and the smaller debris resulting as a by-product from fragmentation would span all smaller classes, and not predominantly the smallest. This suggests that the method used to determine the finest fractions has actually increased the production of these fines.

We verified the hydrocyclone-abrasion hypothesis with the additional experiments under atmospheric pressure, where the collision of the (intact) Belgian polymetallic nodules with a flat plate was studied in detail. In these additional tests, no significant quantity of fines was produced for single impact events up to \( v_f = 8 \text{ m/s} \). Three successive impact events at \( v_f = 4 \text{ m/s} \) showed production of 0.01% of material in the 0–63 \( \mu m \) class, which is more than an order of magnitude less than the amounts found at the NIOZ experiments. This observation supports the idea that abrasion in the hydrocyclone rather than pure impact fragmentation induced the production of fine material.

We have analysed the degradation rates of polymetallic nodules of relevant sizes (equal to the sizes that would be mined in future deep sea mining operations) under relevant pressure and velocity conditions (typical transport velocities would be around \( 4 < v_f < 6 \text{ m/s} \)), and in this way the current data can be used as a starting point for engineering calculations. The results of our experiments contribute to a better understanding of fragmentation of polymetallic nodules in a qualitative and quantitative way, data that was unavailable thus far. Quantitative comparison between the experiments at NIOZ and the additional atmospheric experiments is complicated by the fact that the nodules at NIOZ were sized down to the required size class while at IHC the nodules were left intact. Sized nodules are possibly relatively strong, since they already have broken along the weakest internal fracture planes. This again calls for more detailed study of the mechanical properties of nodules in relation to the fragmentation process. Reflecting on the current state of the art, modelling the fragmentation process using the models discussed in this article requires more data than is currently available and the variance in the current data would give rise to relatively large uncertainty in the outcome.

For improved engineering modelling we anticipate to build further on the work of Chapelle et al. (2004b). The data presented in this article combined with the notion of a lower limit in particle size for impact fragmentation as emerged from the time scale analysis could allow for calculations with a limited breakage matrix. We intend to explore this option in future work.

6. Conclusions and recommendations

The impact fragmentation experiments under large ambient pressure conditions in the centrifugal pump in the pressure tank at NIOZ showed that for ambient pressures in the range of \( 5 \leq p \leq 500 \text{ bar} \) the ambient pressure has no significant influence on the nodule fragmentation.

The experiments showed that nodule degradation in the pump strongly relates to the nodule velocity and the speed of the impeller.
The same result was found with the additional pure impact experiments under atmospheric conditions. The susceptibility of degradation of poly metallic nodules in a centrifugal pump can be analysed with a time scale analysis. The nodule entry velocity and impeller speed are the dominant parameters that determine whether a particle has collisions with the pump impeller nose and blades. Whether a collision will result in fragmentation of the nodule is related to the actual velocities, forces and particle properties. This requires a more detailed investigation of nodule fracturing mechanisms. The time scale analysis predicts the existence of a lower limit in particle size due to fragmentation, but the current experiments were not sufficient to verify this hypothesis.

The relative dominance of the smallest size class (d < 63 μm) in the NIOZ results suggests abrasion of nodules in the hydrocyclone. Additional experiments under atmospheric conditions were conducted to verify whether pure impact fragmentation (enforced by dropping Belgian CCZ nodules through air on a submerged flat plate) would result in large amounts of fines. These experiments resulted in a maximum of 0.01% of material with d < 63 μm after three impacts compared to >1% found after single impact at NIOZ. Abrasion in the hydrocyclone therefor is still thought to have influenced the NIOZ results for the smallest size classes, especially at larger pump speeds.

The average degradation rates found for the sequential experiments at NIOZ are smaller than the averages found for the single passage experiments, just below the lower limits of the single passage experiments. There is no explanation yet for this phenomenon, but for future research it is recommended to look at mechanical properties of nodule fragments related to nodule size. The current research shows that application of single passage data for prediction of multi-passage degradation could lead to overly conservative results. This is an important observation for improved modelling and the design of calculation methods.

The atmospheric experiments at IHC MTI resulted in multiple times larger degradation rates than the rates found at NIOZ. Besides differences in particle size, particle velocity and differences in the impact mechanism (pure impact under atmospheric pressure versus a more complex impact process in the centrifugal pump, with an unknown impact velocity with the impeller blades), another difference is the fact that nodules at NIOZ were sized to impact velocity with the impeller blades), another difference is the fact that nodules at NIOZ were sized to impact velocity with the impeller blades), another difference is the fact that nodules at NIOZ were sized to impact velocity with the impeller blades). Another difference is the fact that nodules at NIOZ were sized to impact velocity with the impeller blades. Whether a collision will result in fragmentation of the nodule is related to the actual velocities, forces and particle properties. This requires a more detailed investigation of nodule fracturing mechanisms. The time scale analysis predicts the existence of a lower limit in particle size due to fragmentation, but the current experiments were not sufficient to verify this hypothesis.

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For engineering calculations it is recommended to explore models that are based on limited data combined with well supported assumptions.

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