



CLOSE-OUT REPORT FOR THE IMPACT OF
HYDROGEN ON NTS OILS AND GREASES
PHASE 2 INNOVATION PROJECT

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[REDACTED]

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[REDACTED]

[REDACTED]

[REDACTED]

LIST OF ABBREVIATIONS

ASME – American Society of Mechanical Engineers

ASTM – American Society for Testing and Materials

EDC – Engineering Design & Consultancy

HE – Hydrogen Embrittlement

HIC – Hydrogen Induced Cracking

HTHA – High Temperature Hydrogen Attack

MCM – M.C.M High Performance Sealing

NGT – National Gas Transmission

NTS – National Transmission System

OEM – Original Equipment Manufacturer

R&D – Research and Development

RFI – Request for Information

SDS – Safety Datasheet

US – United States

WP – Work Pack

LIST OF UNITS

in - inch

mm – millimetre

m.barL/s – millibar litres per second

ppm – parts per million

psi – pounds per square inch

psig - pounds per square inch (gauge)

rpm – revolutions per minute

thou – 1 thousandth of an inch

CLOSE-OUT REPORT FOR THE IMPACT OF HYDROGEN ON NTS OILS AND GREASES PHASE 2 INNOVATION PROJECT

1.0 INTRODUCTION

This technical report details the findings of the work performed by Score Group on the 'Impact of Hydrogen on NTS Oils and Greases – Phase 2' innovation project (NIA_NGT0268) commissioned by National Gas Transmission (NGT).

Phase 1 of 'Impact of Hydrogen on NTS Oils and Greases' project was a desktop exercise carried out by Wood [1], broken down into five Work Packs (WP) with the overall aim to identify areas requiring further experimental research to better understand how the transition from natural gas to hydrogen (hydrogen) would affect maintenance consumables, such as lubricating oils, greases and sealants. Original Equipment Manufacturers (OEM) were contacted to appraise the market's current position regarding hydrogen readiness for these consumables, therefore revealing gaps in the market to explore. In conjunction with this OEM engagement, engineering specifications were reviewed by Wood to identify existing testing regimes to verify consumable products for hydrogen application, leading to their testing propositions for both oils and greases.

Phase 2, therefore, primarily focused on carrying out physical tests broadly based on Wood's proposals, which has been carried out for both oils and greases (sealants). The consumables identified for testing, based on work completed in Phase 1 identifying gas-facing products, have been chosen due to the high frequency of use within NGT's maintenance regimes, therefore providing the greatest immediate impact to current operations, and are listed below, inclusive of references to their applicable Safety Data Sheets (SDS).

Oils

[REDACTED]
[REDACTED]
[REDACTED]

Greases (Sealants)

[REDACTED]
[REDACTED]
[REDACTED]

2.0 BACKGROUND

2.1 Oils

Lubricating oils are an essential maintenance consumable for NGT as they are utilised throughout the National Transmission System's (NTS) rotating equipment, however not all oils used in this equipment would be in contact with the service media, so only gas-facing oils were considered for review. The purpose of the lubrication compounds are to reduce friction, wear and heat between the moving components, namely compressors and turbines with regards to NGT's NTS, and the effectiveness of these compounds depends on their intrinsic physical properties. A good lubricating oil will have:

- An optimal and stable viscosity, which does not fluctuate with temperature or (in this particular case) in the presence of certain gases, such as hydrogen. This ensures that the oil remains able to provide a protective film over the dynamic parts of the rotating equipment without becoming too thin (removal of film) or too thick (increased friction and drag) throughout the system's operation.
- Resistance to chemical degradation, such as exposure to oxygen or (again, in this particular case) hydrogen, ensuring the oil remains in its viscous liquid form and does not break down into undesirable substances.
- Good water separation and rust prevention properties, enabling the oil to expel water and prevent corrosion

The oil testing was subcontracted out to Savant Labs, a United States (US) based laboratory part of the greater Savant Group consortium, who specialise in lubricant & grease testing. Test proposals for the oils were largely in-line with Wood's recommendations and were designed to investigate how the oils' physical properties change upon hydrogen exposure, measuring key variables such as those listed above, detailed fully in Section 6.1.3, before and after exposure in Tannas & King Quantum Pro Oxidation Tester pressure vessel (see Appendix G. The results will determine which (if any) oil would be suitable for use in hydrogen applications, based on their ability to retain their physical properties despite exposure to hydrogen.

2.2 Greases

Sealant (grease) injection can be an effective maintenance strategy for minimising valve leakage to atmosphere, or through the bore, without conducting any intrusive maintenance - but only where the valve has dedicated injection facility ports. The most common places for these ports are at the stem to bonnet interface or at the seat to ball interface (for ball valves), which allows for a grease to be injected from outside the valve, through the pressure boundary and onto the subject sealing interface. Given this can be done without taking the valve out of line, it poses a great advantage over valve removal maintenance regimes as system operation does not need to cease. However, it is only a temporary measure as the leak source (cracks, scratches, scores etc.) is not being repaired. Many sealant compounds have been tried and tested for the oil and gas industry, albeit none have been proven for the seeking nature of hydrogen, hence the requirement for these compounds' effectiveness to be tested. The sealant greases testing was conducted in-house at Score's Glenugie facility in Peterhead.

3.0 SUMMARY AND CONCLUSIONS

- 3.1** A literature review was performed to investigate current knowledge for oils and greases with hydrogen exposure, but information was found to be sparse within the oil and gas industry.
- 3.2** NGT's 3-off most utilised oils in their rotational equipment were sourced by Score and shipped [REDACTED] to be subject to performance testing upon hydrogen exposure.
- 3.3** [REDACTED] was the top performing oil for both non-exposed and hydrogen exposed tests, showing no reduction performance to any reportable level when exposed to hydrogen.
- 3.4** [REDACTED] oil was the most affected oil, where 3 tests revealed a performance change between the control sample and the hydrogen exposed sample.
- 3.4.1** Two out of three of these cases actually show an increase in performance of the oil when exposed to hydrogen over the control sample, however despite this improvement, the results were still inferior to the other 2 oils' performances.
- 3.5** NGT's 3-off most utilised sealant injection compounds in their system were sourced by Score and subject to performance testing with forming gas (5% Hydrogen 95% Nitrogen) using a Score manufactured test rig to determine their sealability across 7 different damage levels. Leakage was quantified using Inficon's Extrima Hydrogen Leak Detector (see Appendix H).
- 3.5.1** All 3 sealant compounds were found to reduce the leakage rate of hydrogen when compared to a baseline leakage rate without a sealant compound present, but the extent of their effectiveness depended on pressure application and the damage level, where each compound offers a unique strength.
- 3.5.2** The 'damage' consisted of a singular vertical score on the test rig sealing interface, which got increasingly deeper with each damage level, ranging from level 1 at 0.0125mm (0.0005in) to level 7 at 1.75mm (0.070in), at which point the score resembled more of a notch.
- 3.5.3** The first 3 damage levels exhibited 0 leakage past the test rig O-Ring, the material of which (MCM Grade N9012) was selected based on Score's previous R&D project for NGT Titled 'Hydrogen Impact on NTS Valves & Maintenance - NIA_NGT0227' [2]. This shows that this O-Ring grade has sealing abilities up to 0.1mm (0.004in) pit depths.
- 3.5.4** Damage levels 4-7 proved too severe for the O-Ring to seal against, hence the sealant injection compounds could be introduced to reduce the leakage, and therefore only damage levels 4-7 provided useful data for evaluating the compounds' effectiveness.

[REDACTED]

[REDACTED]

[REDACTED]

- 3.8.1** This sealant was not the best performing compound at any damage level but did not exhibit the extreme highs and lows in performance that the other two compounds did.

- 3.9** A high-level summary of the sealant compounds performance can be found in Table 7 within Section 7.2.1.

4.0 RECOMMENDATIONS

4.1 Oils

- 4.1.1 [REDACTED] can be utilised in NGT's NTS after the introduction of hydrogen as there are no signs of performance degradation upon exposure to hydrogen.

- 4.1.3 Further testing to be carried out on [REDACTED] (from the identified oils in this scope) using a select set of rotating equipment. These tests can be used to highlight the significance of the property changes shown in the [REDACTED] test report of these two oils and what likely physical impact they may have in-situ on NGT's rotating equipment.

- 4.1.4 Further oil testing, similar to what was completed in this report, to be carried out for other oils that are deemed similar to the [REDACTED] range regarding physical properties (such as relative density, kinematic viscosity etc.). This can be carried out to find an oil with similar hydrogen resilience to [REDACTED], but compatible with the equipment better suited to the [REDACTED] range oil properties, in the case where the further testing detailed in Section 4.1.3 reveals the [REDACTED] range cannot be utilised by NGT.

- 4.1.5 Temperatures at which rotational equipment can reach are to be established by NGT to determine if High Temperature Hydrogen Attack (HTHA) may be a concern. Score advise that if temperatures above 400°C are reached, HTHA can be an issue, which may be exacerbated by the oil's gas retention.

4.2 Greases

- 4.2.2 Score recommend that further investigative work is undertaken into sealant performance on the 36" x 600# [REDACTED] valve from Score's previous R&D project for NGT [2], to allow for seat to ball interface testing.

5.0 LITERATURE REVIEW

Hydrogen possesses several physical and chemical properties that distinguish it from typical hydrocarbons, including small molecular size, high diffusivity, low viscosity and high permeability through materials. These properties increase the likelihood of leakage through sealing mechanisms and influence tribological interactions within mechanical equipment. Research into hydrogen compatibility has expanded significantly over the past two decades, focusing primarily on metallic materials which are subject to hydrogen embrittlement and on polymeric materials used as seals. However, relatively little work has addressed the performance of maintenance consumables, such as lubricating oils and valve sealant injection compounds which are widely used in natural gas systems. Lubricants are essential for protecting rotating equipment such as compressors and turbines, while sealant injection compounds are routinely used as temporary mitigation measures to reduce valve leakage. As hydrogen networks develop, understanding how these consumables behave in hydrogen environments becomes increasingly important [3].

Due to the small size of the hydrogen molecule, it can present challenges with maintaining a pressure boundary as the gas can permeate through materials as well through the smallest leak paths. The “particle size” of a gas can be defined as the molecular diameter, however, for gas flow in small leakage paths the “kinetic diameter” is used. The kinetic diameter is related to the mean free path of the molecule which determines whether the gas will be able to leak through very small paths and gives a measure of how the molecule will interact with its surroundings and other molecules. This low-level flow is known as Knudsen Flow or Molecular Streaming. Typical kinetic diameters are given below in Table 1. Compared with methane, hydrogen has a significantly smaller kinetic diameter and lower viscosity. This enables hydrogen to diffuse through microstructural defects and porous materials more readily than typical hydrocarbon molecules.

Molecule	Molecular Mass	Kinetic Diameter (pm or 1×10^{-12} m)
Hydrogen	2	289
Helium	4	260
Methane	16	380
Nitrogen	28	364
Propane	44	430
Chlorine	70	320

Table 1 : Molecular Mass and Kinetic Diameter

Permeation of hydrogen through materials occurs primarily through diffusion mechanisms. In polymers hydrogen molecules can migrate directly through the polymer matrix, whereas in metals hydrogen typically dissociates into atomic hydrogen before entering the crystal lattice. The difference in transport mechanisms results in varying susceptibility to hydrogen exposure. The high diffusivity of hydrogen also means that even minor imperfections in sealing surfaces can result in measurable leakage. Consequently, sealing systems designed for natural gas service may experience increased leakage when exposed to hydrogen or hydrogen-blended gas streams. The behaviour of elastomeric seals exposed to hydrogen has been extensively reviewed, elastomers are widely used as O-Ring seals and seal components in valves, compressors and other pressure systems. A review conducted by Zheng et al. examined the effect of high-pressure hydrogen on elastomeric sealing materials used in hydrogen infrastructure [4] [5]. The study highlighted several degradation mechanisms including hydrogen permeation, swelling, mechanical property degradation and rapid gas decompression damage. Hydrogen permeation into elastomers occurs due to pressure-driven diffusion through the polymer matrix. The amount of absorbed hydrogen increases with pressure and temperature and is often proportional to the applied pressure

according to Henry's Law. As hydrogen accumulates within the material, swelling may occur which alters the mechanical properties and sealing behaviour [6].

Rapid Gas Decompression (RGD) is a critical failure mode observed in hydrogen sealing systems. When a hydrogen-saturated elastomer is depressurised rapidly, dissolved hydrogen may then nucleate within the polymer matrix, forming internal voids that can then propagate as cracks. These cracks reduce the sealing performance and may lead to a catastrophic failure. Recent reviews of O-Ring seal degradation mechanisms in hydrogen environments confirm that hydrogen permeation, swelling and decompression damage remain significant risk factors to long term reliability of elastomeric seals in hydrogen service and underscore the importance of carefully selecting seal materials that are suitable for the service. While there has been significant research carried out on elastomeric materials themselves, relatively little work has examined how damaged sealing interfaces interact with hydrogen or how sealants typically utilised to mitigate leakage perform in hydrogen service. In addition to the effects upon a material's physical properties, hydrogen environments can also influence tribological behaviour through changes in surface chemistry. Hydrogen is a strongly reducing gas and can suppress oxide formation on metal surfaces. Since many tribological systems rely upon oxide layers to stabilise friction and wear behaviour, the absence of these films may alter wear mechanisms. Experimental studies on polymer-metal contacts have demonstrated significant changes in tribological behaviour under hydrogen environments. For example, investigations of PTFE sliding against steel in hydrogen showed increased wear rates and altered transfer film formation due to hydrogen reducing effect on surface chemistry [7] [8]. The tribological behaviour of sealing interfaces is particularly important for valve applications. Repeated actuation causes sliding contact between sealing surfaces, and any changes of friction or wear behaviour may affect operating performance over time.

Lubricating oils are critical to the operation of rotating equipment such as compressors, turbines and pumps used within the National Transmission System (NTS). Hydrogen exposure may influence lubricant performance through several mechanisms such as the dissolution of hydrogen within the lubricant. Hydrogen solubility in liquids depends on pressure, temperature and fluid chemistry. Dissolved hydrogen may influence lubricant properties such as viscosity, air release and foaming tendency. Research examining tribological contacts in hydrogen environments has demonstrated that lubricants can influence hydrogen-related degradation processes. Certain lubricant films may reduce hydrogen ingress into metallic surfaces limiting the exposure of fresh metal surfaces during sliding contact [6]. However, most available research has focused on hydrogen combustion engines or laboratory tribology experiments rather than industrial compressor systems as used within the NTS. Consequently, relatively little data exists concerning the behaviour of commercial compressor oils exposed to hydrogen gas environments. Additional research is required to determine whether commonly used industrial lubricants maintain their performance characteristics when exposed to hydrogen service conditions [9].

Typically, leakage occurs through damaged sealing surfaces such as scratches, corrosion pits and erosion damage which create leakage paths that bypass the intended sealing mechanism. The leakage across the sealing interfaces is strongly influenced by defect geometry, including the overall depth of the defect, the width and orientation relative to sealing direction. Even a relatively minor surface defect may produce measurable leakage when sealing hydrogen due to the gas's high diffusivity and low viscosity. Experimental investigations have confirmed that variations in surface roughness and defect morphology can significantly influence sealing performance. Evaluating sealing behaviour across a range of defect geometries is important when assessing hydrogen compatibility of sealing systems. Despite this, most existing studies have focused on simplified sealing geometries rather than realistic valve assemblies [10].

Valve sealant injection compounds are commonly used in the oil and gas industry as a maintenance strategy for mitigating valve leakage without removing valves from service. These compounds are typically grease-based formulations injected through dedicated valve ports. Once injected, the sealant spreads across the sealing interface and fills surface defects, forming a temporary sealing barrier capable of withstanding high-pressure differentials. Products such as [REDACTED] are widely used in natural gas transmission systems. Despite the widespread use of these compounds, there is very limited peer-reviewed research investigating their performance in hydrogen environments. Most available information originates from manufacturer documentation rather than independent experimental studies. Consequently, the effectiveness of conventional valve sealant injection compounds in mitigating hydrogen leakage remains uncertain [11].

Previously Wood PLC investigated the impact of hydrogen on lubricating oils, greases, and sealant injection compounds used within the National Transmission System (NTS) for National Gas Transmission (NGT). The primary objective of the study was to identify gas-facing lubricants and sealants used within the NTS and assess their suitability for hydrogen service through a combination of literature review, manufacturer engagement, and proposed experimental testing methodologies. A database of consumables was compiled, and manufacturers were contacted to determine whether hydrogen compatibility data existed for their products. However, the study found that very limited information was available from both literature and OEMs, with most manufacturers unable to provide evidence supporting hydrogen compatibility. Engagement with equipment OEMs further revealed that, in many cases, lubricants are not expected to come into direct contact with the process gas under normal operating conditions. For example, compressor systems used within the NTS are typically designed such that lubricating oils are isolated from the gas stream, particularly in dry seal or electrically driven compressor configurations. As a result, the risk to lubricants is considered to be indirect in many applications. However, this assumption may not hold under abnormal conditions such as seal failure, transient operation, or contamination pathways. In contrast, sealant injection compounds were identified as inherently gas-facing products and therefore represent a more critical area of concern. Despite this, the study highlighted a significant lack of available data regarding the performance of sealants in hydrogen environments. Manufacturer engagement confirmed that some suppliers currently do not have sealants qualified for hydrogen service and are still in the process of developing suitable products. Furthermore, industry standards such as IGEM guidance were found to contain minimal information on oils and greases, although they do emphasise the need for qualification of non-metallic materials for hydrogen service. The study also identified that existing literature on hydrogen compatibility of oils and greases is sparse, with no clear evidence either supporting or rejecting their suitability for hydrogen exposure. This reinforces the observation that maintenance consumables have not been a primary focus of hydrogen research compared with structural materials and sealing elements [1].

To address these knowledge gaps, the study proposed a series of laboratory-based testing methodologies to evaluate the impact of hydrogen on key material properties. For lubricating oils, recommended test parameters include viscosity, oxidation stability, flash point, and emulsification or gas solubility behaviour. For sealants, permeability and hardness were identified as critical properties influencing performance under hydrogen exposure. In addition to laboratory testing, the study evaluated the feasibility of asset-level testing and in-service monitoring. It was concluded that in-service monitoring of lubricants represents a practical and cost-effective method for assessing long-term performance under real operating conditions, particularly as existing monitoring infrastructure already exists within the NTS. Overall, the findings of this study highlight a critical gap in current knowledge. While hydrogen compatibility has been widely investigated for structural and sealing materials, there remains a lack of validated data for lubricants and sealant injection compounds used in gas transmission systems. The study therefore reinforces the need for targeted experimental research to support the safe transition of existing infrastructure to hydrogen service.

6.0 WP2 – EXPERIMENTAL TEST PROGRAMME

6.1 Oils

6.1.1 Testing Schedule

██████████ instructed Score that their testing schedule would comprise of exposing the sample oil to pure hydrogen in the Oxidation Tester pressure vessel (see Figure 1 & Appendix G), pressurised to 100 psi and rotated at 100 rpm for 24 hours. This ensures the oil is preconditioned with an even exposure across its entire volume to hydrogen for the tests to follow (see Section 6.1.3). hydrogen exposed oil test results would then be compared to their respective control sample of the same oil grade, therefore providing a suitable benchmark value to determine whether hydrogen exposure affects the oils' properties in any meaningful way. The following oils were to be tested:

████████████████████
████████████████████
████████████████████



Figure 1: Tannas & King Quantum Pro High Pressure Oxidation Vessel

6.1.2 Test Parameters

Exposure Gas:	100% hydrogen
Exposure Time:	24 hours
System Pressure:	100 psi
Rotational Speed:	100 rpm

6.1.3 Test Types

Tests performed to evaluate the three different oils were conducted as per the list below, most of which were detailed in Wood's test proposal from their Phase 1 desktop exercise within "WP5: TEST & VALIDATION PLAN PROPOSAL [1]". There are some extra inclusions to Wood's proposal, indicated with an asterisk (*) and two exclusions (D943-02 Oxidation Test & D7843-21 Varnish Test). The below list was decided upon with assistance from [REDACTED] taking their expert advice on useful tests that they could conduct on board, whilst still pertaining to the original scope proposed by Wood in Phase 1 of the investigative project as much as possible.

1. ASTM D445 KV 40 °C Viscosity Testing [12]
2. ASTM D4052 40 °C Density of Fluid * [13]
3. ASTM D3427 Air Release at 50 °C (air entrainment test) [14]
4. ASTM D892 Sequence I Foam test at 24 °C * [15]
5. ASTM D4172 4-Ball Wear Testing - Method B * [16]
6. ASTM D7563 Water Emulsification Test [17]
7. ASTM D92 Induced Flash Point Test [18]
8. ASTM D665 Rust Prevention (Distilled water method) * [19]

6.1.4 Salient Test Results

[REDACTED] reported the results to Score Engineering on 27th February 2026 via a PowerPoint slide document, provided in Appendix I. It was noted that over all the 24 tests conducted on the hydrogen conditioned oils (8 test types over 3 different oils), 4 tests showed a reportable differing result to their respective control example. Table 2 below indicates which tests showed significant changes in performance when the oil was exposed to hydrogen, denoted by an 'X'.

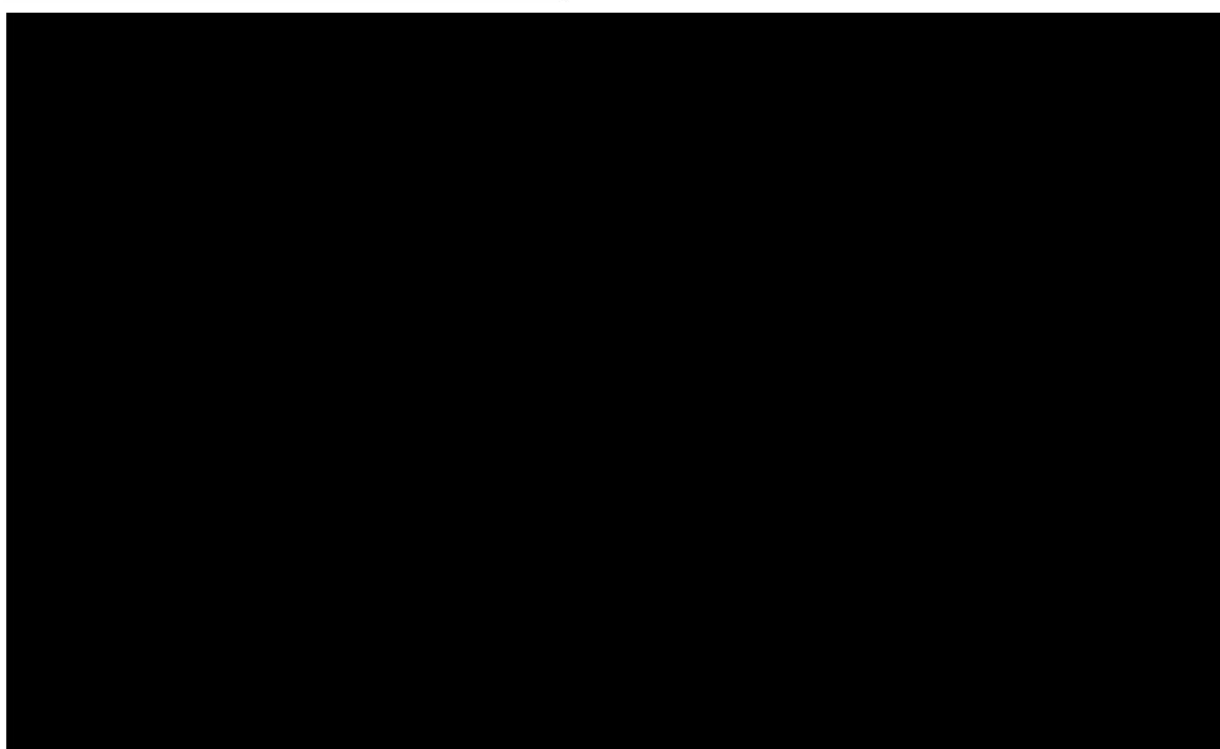
Test	Oils Showing Performance Changes with hydrogen Exposure		
	[REDACTED]	[REDACTED]	[REDACTED]
D445 KV Viscosity Testing at 40°C			
D4052 Density of Fluid at 40°C			
D3427 Air Release at 50°C		X	X
D892 Sequence I Foam test at 24°C		X	
D4172 4-Ball Wear Testing - Method B		X	
D7563 Water Emulsification Test			
D92 Induced Flash Point Test			
D665 Rust Prevention			

Table 2: [REDACTED] Oils Testing Salient Results

It can be seen from Table 2 that [REDACTED] displays no change in performance when exposed to hydrogen across all tests, whereas [REDACTED] has 3 properties where performance can be expected to change upon hydrogen exposure. This section will showcase the differing results, whereas all other tests that showed comparable results between the hydrogen conditioned oils and their respective control examples can be found in Savant Labs' slides in Appendix I.

6.1.4.1 Air Release Test Results

[REDACTED], air release tests were completed in accordance with ASTM D3427 and "measure the rate of air release from petroleum oils at 50 °C. High rates of entrainment can result in accelerated oxidation, pump cavitation, compression change and film strength reduction". As it can be seen in Graph 1, the time taken to release the air (Y-axis) remains the same for the [REDACTED]



Graph 1: Air Release Test Results

6.1.4.2 Foam Test Results

Foam tests are used to determine how readily an oil forms foam when air is blown through a diffuser into the oil, and also how long it takes for the foam to collapse. Foaming is not a desirable tendency for the oil as it reduces the oil's ability to protect the metallic materials as the consistency of the oil is not optimal.

As shown in Table 3 [REDACTED] showed a tendency to foam during both control and hydrogen tests, actually performing better with hydrogen exposure, taking over a minute for the foam to collapse and return to its original consistency. Considering both the other oils showed no signs of foaming, it can be concluded that although [REDACTED] showed better results when conditioned with hydrogen over air, there are still adverse reactions that are undesirable within NGT's NTS.

Sample ID:												
	S20251217-016				S20251217-019				S20251217-017			
Tendency (l) @ 24.0°C mL	0	0	0	0	160	200	125	150	0	0	0	0
1 Minute (l) Stability mL	0	0	0	0	20	50	0	0	0	0	0	0
10 Minutes (l) Stability mL	0	0	0	0	0	0	0	0	0	0	0	0
Collapse Time (l) second(s)	0	0	0	0	30	87	53	60	0	0	0	0

Table 3: Foam Test Results

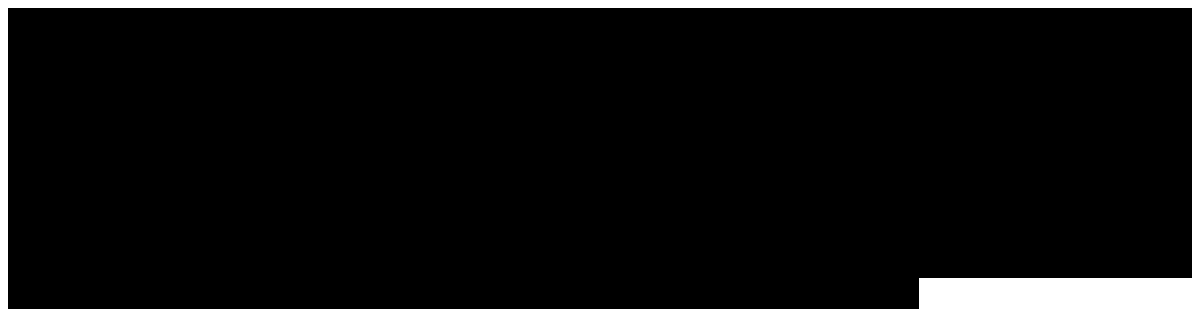
6.1.4.3 – 4-Ball Wear Results

This test uses the average wear scar diameter over 3 stainless steel balls, created by a larger fourth ball, which are coated in the subject oil and held in a cradle. This test is used to determine wear resistance under applied load, boundary film stability and the effectiveness of anti-wear additives. This will be imperative when considering oils to be used in rotational equipment within NGT's NTS such as turbines and pumps. Results from the 4-ball wear test can be seen in Table 4 below,

Sample ID:								
	S20251217-016	0.437	0.427	0.407	0.407	0.424	0.415	0.419
		0.496	0.461	0.512	0.471	0.569	0.538	0.506
	S20251217-019	0.392	0.388	0.415	0.424	0.373	0.363	0.393
		0.410	0.400	0.415	0.407	0.422	0.400	0.409
	S20251217-017	0.586	0.646	0.516	0.516	0.666	0.571	0.514
		0.761	0.818	0.766	0.872	0.768	0.869	0.866
		0.761	0.711	0.475	0.891	0.876	0.944	0.761
	S20251217-020	0.527	0.600	0.656	0.537	0.536	0.521	0.596
		0.641	0.617	0.663	0.660	0.538	0.522	0.666
	S20251217-018	0.519	0.496	0.541	0.511	0.466	0.434	0.495
		0.544	0.514	0.492	0.450	0.510	0.476	0.468
	S20251217-021	0.527	0.489	0.503	0.492	0.464	0.430	0.483
		0.546	0.523	0.512	0.491	0.471	0.447	0.496

Table 4: 4-Ball Wear Test Results

6.1.5 Discussion



Also, given these oils are employed in rotational equipment, high temperatures may be experienced within these components which, when paired with prolonged hydrogen exposure, can lead to risks associated with High Temperature Hydrogen Attack (HTHA), in addition to Hydrogen Embrittlement (HE) and Hydrogen Induced Cracking (HIC) [20], “High temperature hydrogen attack (HTHA) is an irreversible deterioration of the mechanical properties of steel due to the reaction of hydrogen with carbon at high pressures and temperatures, typically in excess of 400°C, for prolonged periods”. Therefore, temperatures within NGT’s rotational equipment shall be assessed to determine if HTHA resistant materials should be utilised.

The 4-ball wear test is a useful test to observe how stainless steel will deteriorate over time under load and how this deterioration is affected when the oil is exposed to hydrogen. The results are a direct measure of physical wear patterns, as opposed to measuring changes in the oils’ properties and estimating the impact these changing properties would have on a physical object (i.e. density, viscosity, air release etc.). Essentially, this test removes the theoretical aspect and proceeds to directly measure the physical impact and what could be expected in-service.

Given this will directly impact rotational equipment’s ability to operate efficiently and effectively over its intended service life, these results are an ideal marker to indicate which oil should be employed throughout NGT’s NTS. Again, the clear standout oil [REDACTED], boasting the lowest average scar diameter of all three oils. Interestingly, this oil shows a lower scar diameter with the hydrogen conditioned oil (0.393mm to 0.409 mm) over its control counterpart (0.419mm to 0.506mm), yielding a scar diameter reduction of up to 23.72%. On the contrary, [REDACTED] results were extremely inconsistent as [REDACTED] were unable to get repeatable results. This indicates an unreliable ability to provide wear resistance, albeit there were signs that exposure to hydrogen did assist reliability and performance, but not to the levels of [REDACTED]. Finally, the performance of [REDACTED] o [REDACTED] was reliable and offered no reportable difference between hydrogen conditioned and control sample oils, where the average scar diameters did not vary more than 0.015mm. but were around 22% larger than [REDACTED]

6.2 Greases

6.2.1 Testing Schedule

Due to costs, logistics and applicability, the testing regime proposed by Wood for these compounds could not be followed as strictly as they were for the oils, where emphasis was placed more on product performance rather than physical property changes of compounds. The proposal from Wood involved measuring hardness levels of the sealant, where the scale starts at “extra soft” (the equivalent of a marshmallow) which, given sealant greases are more of a paste-like substance, would not be wholly applicable. The selected sealants for testing do not harden or ‘cure’, but instead remain a viscous fluid, which can fill the leakage inducing gaps and cracks, thereby reducing the leakage rate.

Also, as sealant injection compounds are typically used as a temporary measure for emergency sealing, their main purpose is to provide a quick sealing solution until the next available chance to remove the valve for repair. On this basis, the sealing performance upon its initial introduction to hydrogen takes precedence over effects of long-term exposure, hence the testing programme was altered to reflect this.

Score’s test proposal, 4342 Rev 0^[2] [21] was to design a sealant injection annulus test rig and subject this sealing arrangement to a series of controlled damage, simulating surface finish defects that a valve would likely see in-line over the course of its service life. By measuring the leakage rate before and after the inclusion of sealant injection compounds, the expected leakage mitigation performance for each compound could be determined. A general overview of the testing steps can be found listed below:

1. Test rig subject to forming gas pressure test at 25 barg increments, up to 113 barg (1.1x ASME B16.34 [22] Group 1.2 600# rating), without sealant grease. Leakage measured using Inficon Extrima hydrogen Leak Detector.
2. Test rig depressurised and injected with [REDACTED] to repeat step 1 to detect change in baseline leakage. Test rig depressurised, disassembled and sealant grease cleaned out.
3. Repeat Step 2 for the remaining two sealant compounds.
4. Test rig sent to Score Machine Shop to have the next damage level manufactured to seal face, then returned to Score’s Glenugie facility to repeat Steps 1 - 3 in full.

This was deemed an appropriate methodology by Score to accurately determine how effective sealant injection compounds will perform in line when NGT would inject to minimise leakage to atmosphere, thereby preferred over testing the sealant’s permeation and hardness properties.

6.2.2 Test Rig – Plate Modifications

During a previous NGT research and development (R&D) scope conducted by Score (Hydrogen Impact on NTS Valves & Maintenance - NIA_NGT0227 // Score Job Number 665997 EDC [2]), Score manufactured two rigs to test ex-service O-Rings. One rig was manufactured based on the body to adaptor sealing arrangement, whereas the other rig was based on the bonnet to stem sealing arrangement, both for the 36" x [REDACTED] subject ball valve. The bonnet to stem plate was chosen to modify for sealant injection trials based on its smaller size for easier machining, transportation and handling. Comprising of two plates, one plate incorporated the geometry of the valve bonnet (bonnet bore with internal O-Ring grooves) and the other the geometry of the stem (stem plain outer diameter).

The stem plate (see Figure 2) plain outer diameter spigot was modified to include 3-off grooves (see Figure 3), where their purposes are detailed below. The bonnet plate (see Figure 4) was modified to remove the original internal O-Ring grooves and make the bore a solid diameter, ready to receive the scratch/score damage. This was completed by removing material from the inner diameter to remove the grooves, then welded back up to the original inner diameter as a plain solid diameter without grooves. In addition to the bore being smoothed out, this plate was also modified to accommodate sealant injection ports. The face O-Ring groove which would house the O-Ring to provide a boundary seal with the other plate remained the same as per original manufacture.

Modification drawings for the stem plate and bonnet plate can be seen in Figure 5 & Figure 6 respectively, whereas a Solidworks cross sectional model of the assembly conveying the sealing arrangement can be seen in Figure 7, Figure 8 and Figure 9.

6.2.2.1 O-Ring Groove

The bottom groove, closest to the large flat mating face of the plate, is to accommodate an O-Ring which created a lower boundary for the sealant grease, essentially representing either a seat insert or stem to bonnet O-Ring. Given the manufactured damage to the bonnet plate would align with this O-Ring, any forming gas that passed by the sealant barrier was expected to also pass by the O-Ring and into the tell-tale port but still retaining the sealant grease to form its boundary.

6.2.2.2 Sealant Grease Annulus

The middle groove is the sealant annulus, a channel for the sealant grease to spread around the plate diameter and create a barrier that was to be tested.

6.2.2.3 U-Cup Seal Groove

The top groove housed a unidirectional U-Cup seal, allowing forming gas pressure to pass by it yet retaining the sealant grease to form the upper barrier. This works in tandem with the lower O-Ring to create the sealant grease housing but still allows pressure to enter the system to allow for a valid test. Had this seal been bi-directional, the test pressure would not be able to reach the sealant grease, thereby creating a false 0 leakage reading during tests. It was imperative that a sealing arrangement allowed for system pressure to build and reach the sealant grease without letting the grease escape its channel.



Figure 2: Stem Test Plate (1)

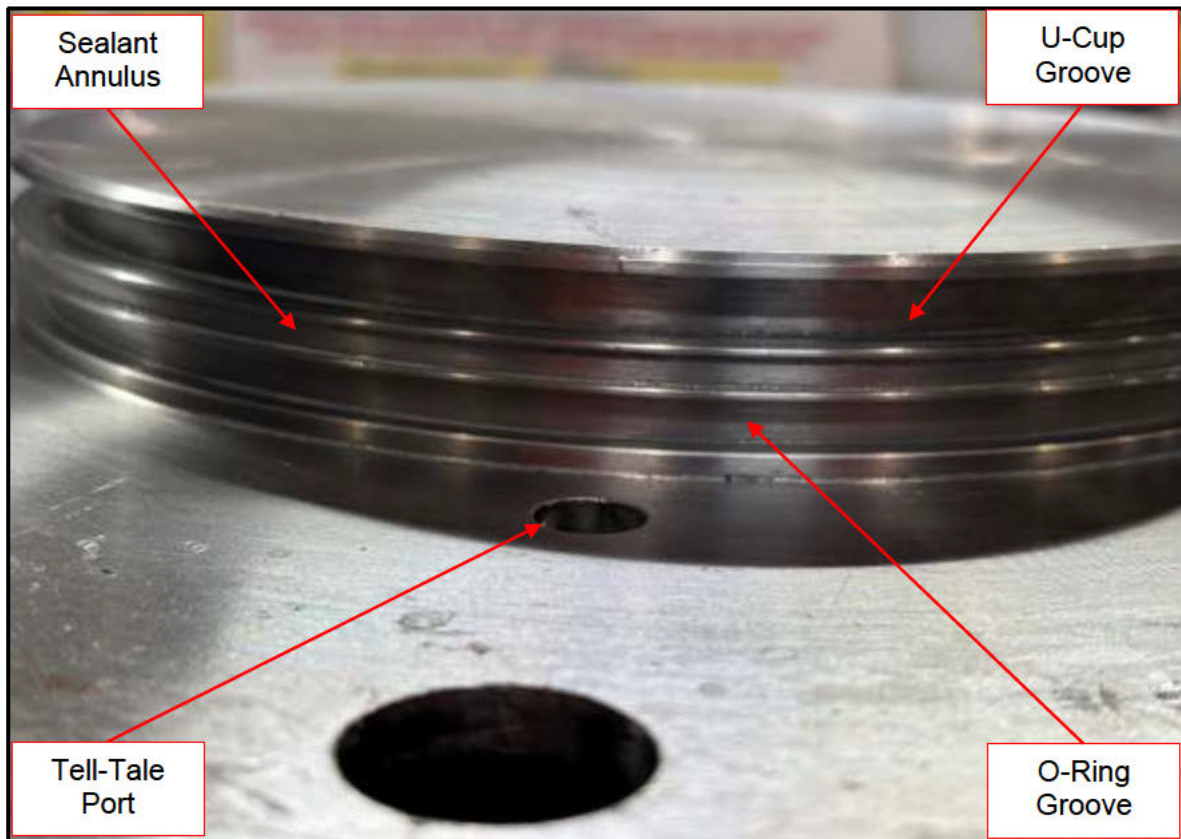


Figure 3: Stem Test Plate (2)

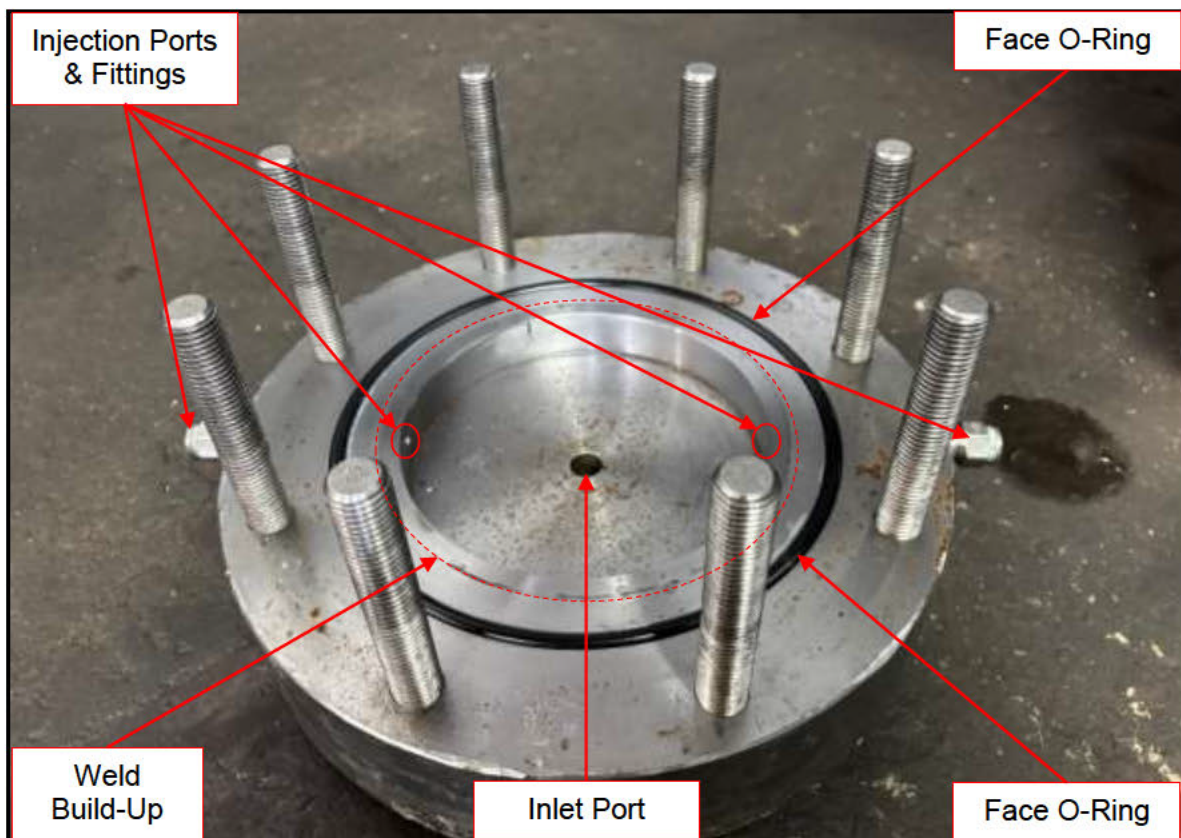


Figure 4: Bonnet Test Plate

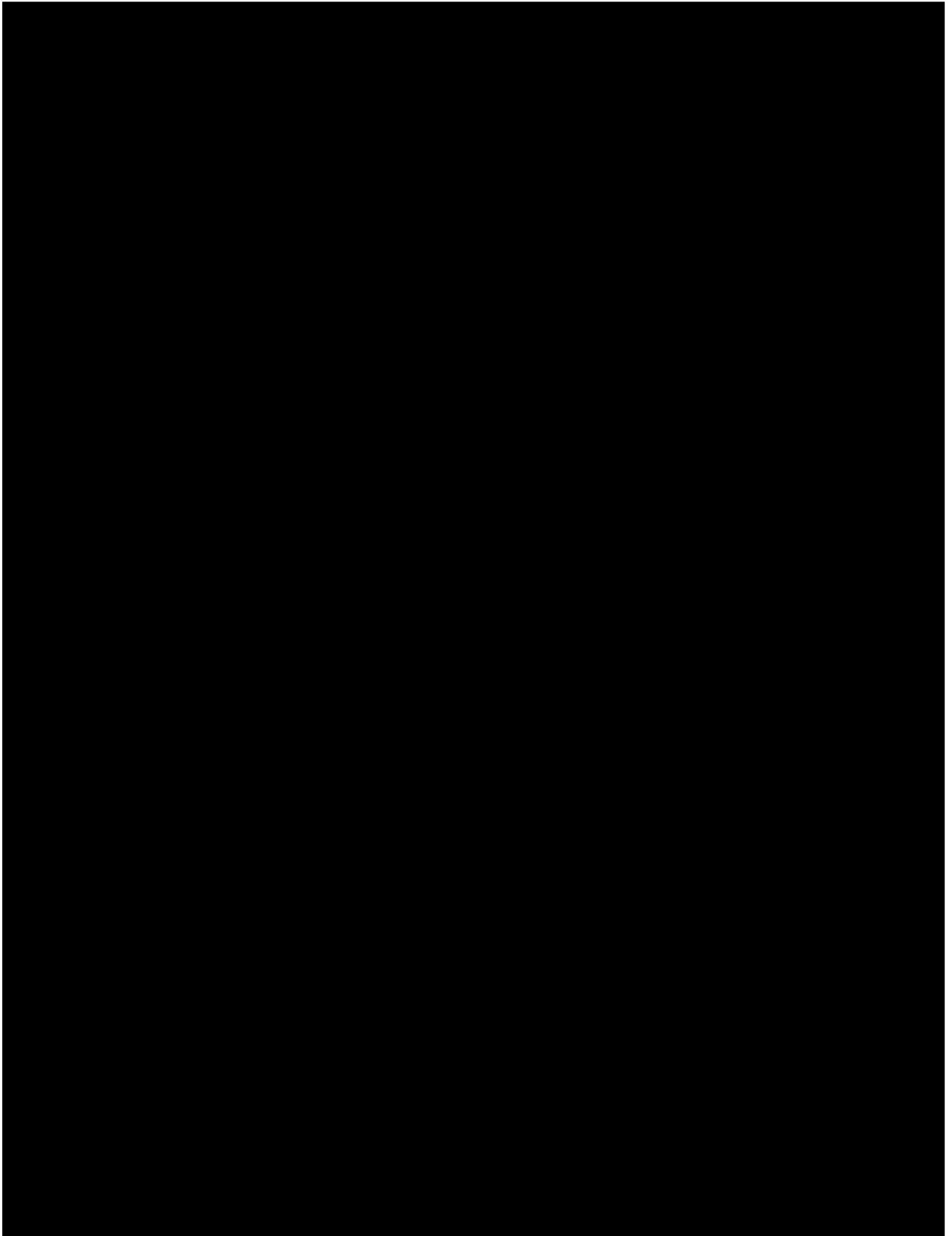


Figure 5: Stem Test Plate Modifications

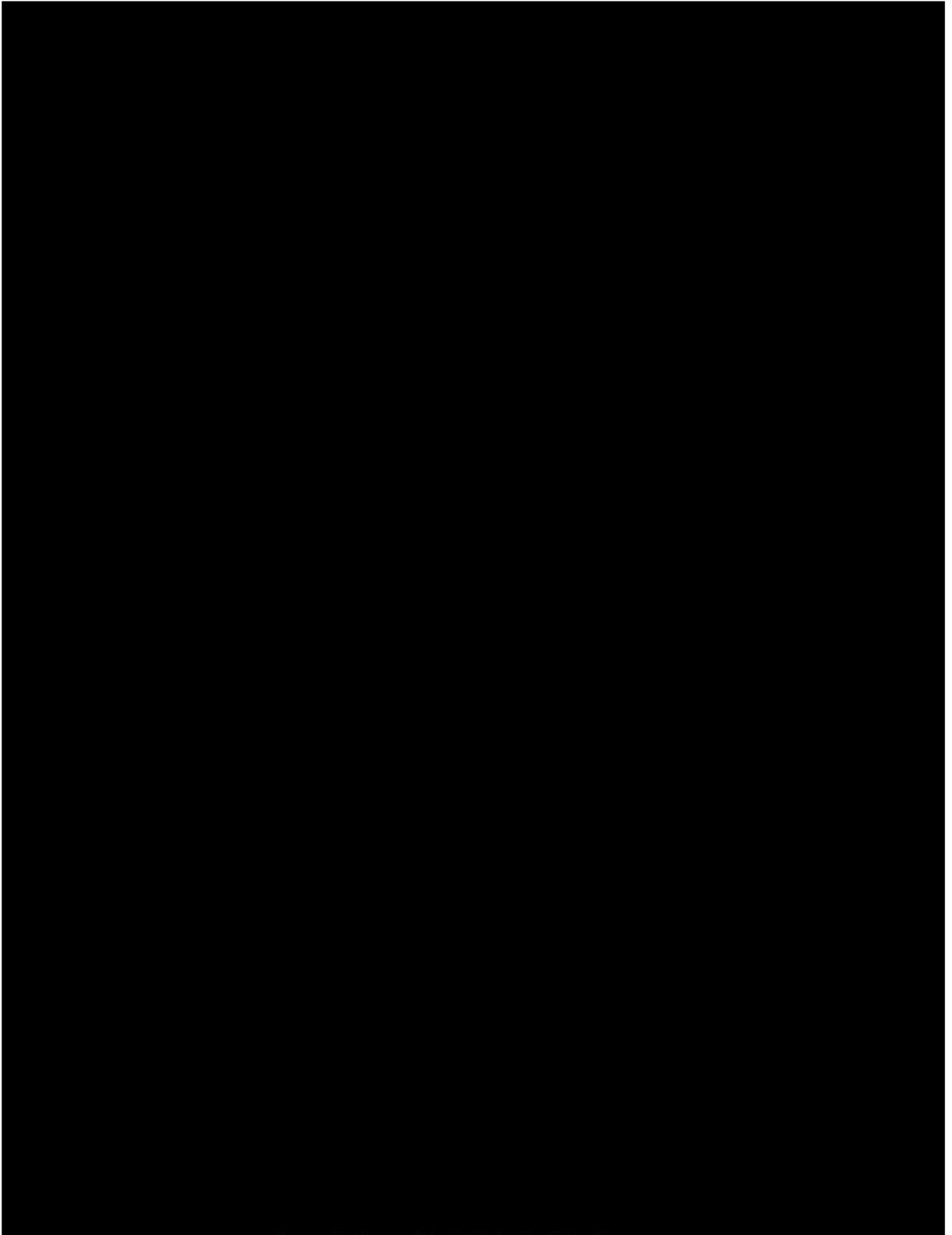
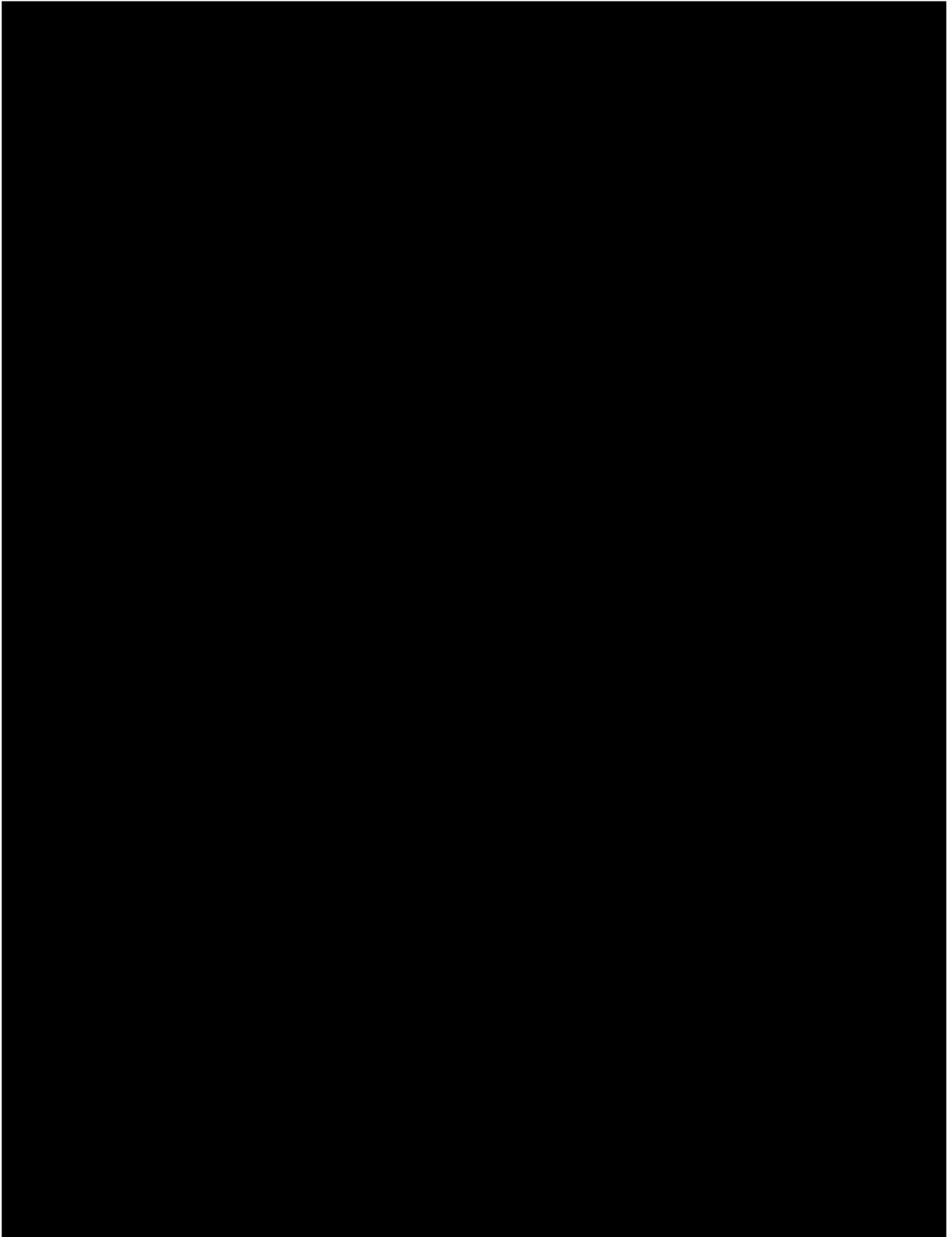


Figure 6: Bonnet Test Plate Modifications



6.2.3 Test Rig – Manufactured Damage

The 'bonnet' test plate which contains the sealant injection ports received a vertical score on the sealing face to represent in-line damage (see Figure 9), which was incrementally worsened after each test cycle, as per Table 5 below. The first damage level was decided upon based on a previous failure investigation conducted by Score [23]. Pit depths from a trunnion bore, trunnion and seat pocket were measured, the deepest of these being 0.0125mm (i.e. damage level 1), hence damage began at this depth. Damage was manufactured on the test plate fitted stationary to a lathe, where a small scratch using a cutting tool was completed by a machinist, the depth of which was shown on a digital readout to ensure accuracy. The depth of the scratch was increased for each damage level, again being controlled by the digital readout on the lathe. Images of the first damage level being made in the lathe can be seen in Figure 10, whereas the resultant damage for each damage level can be seen in Figure 11 to Figure 16, albeit images of level 2 were excluded in error.

Defect Stage	Depth (mm)	Depth (thou)
1	0.0125	0.5
2	0.0500	2
3	0.1000	4
4	0.2500	10
5	0.5000	20
6	1.0000	40
7	1.7500	70

Table 5: Defect Depth Proposal

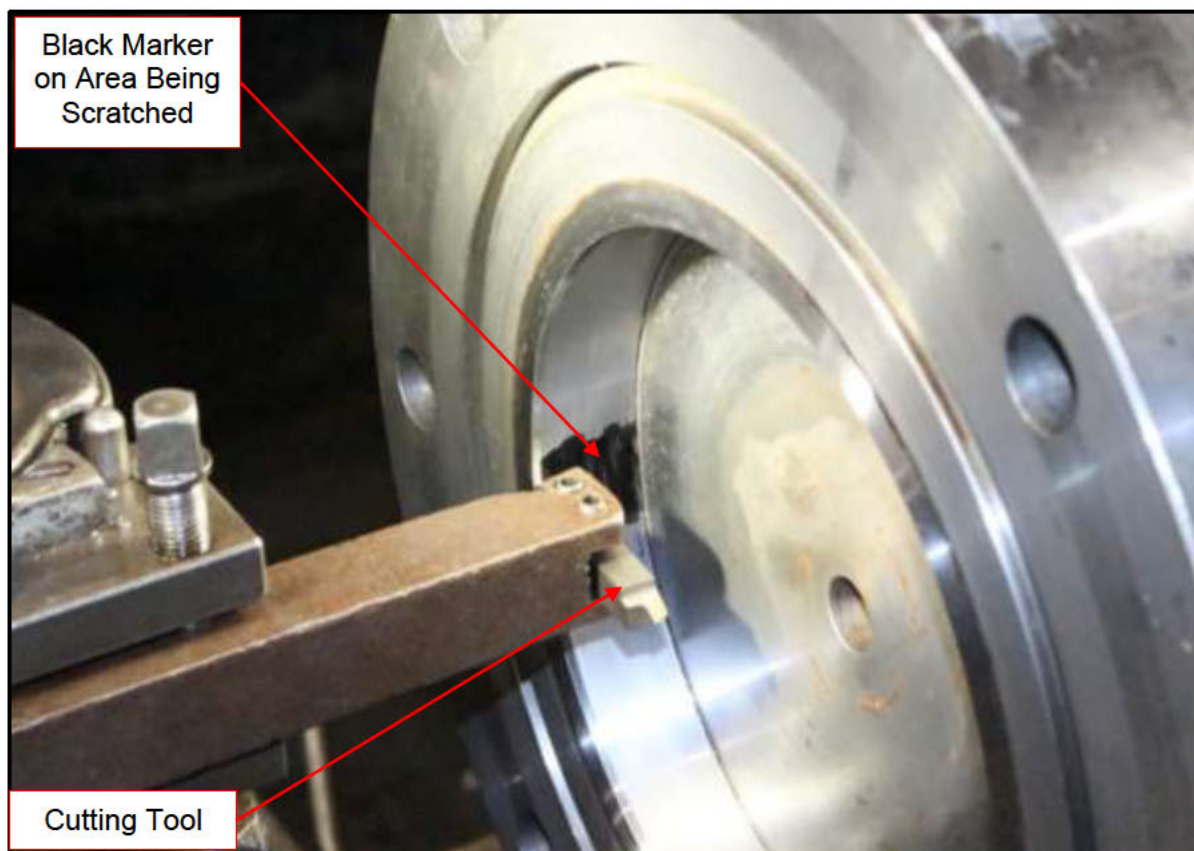


Figure 10: Bonnet Test Plate in Lathe

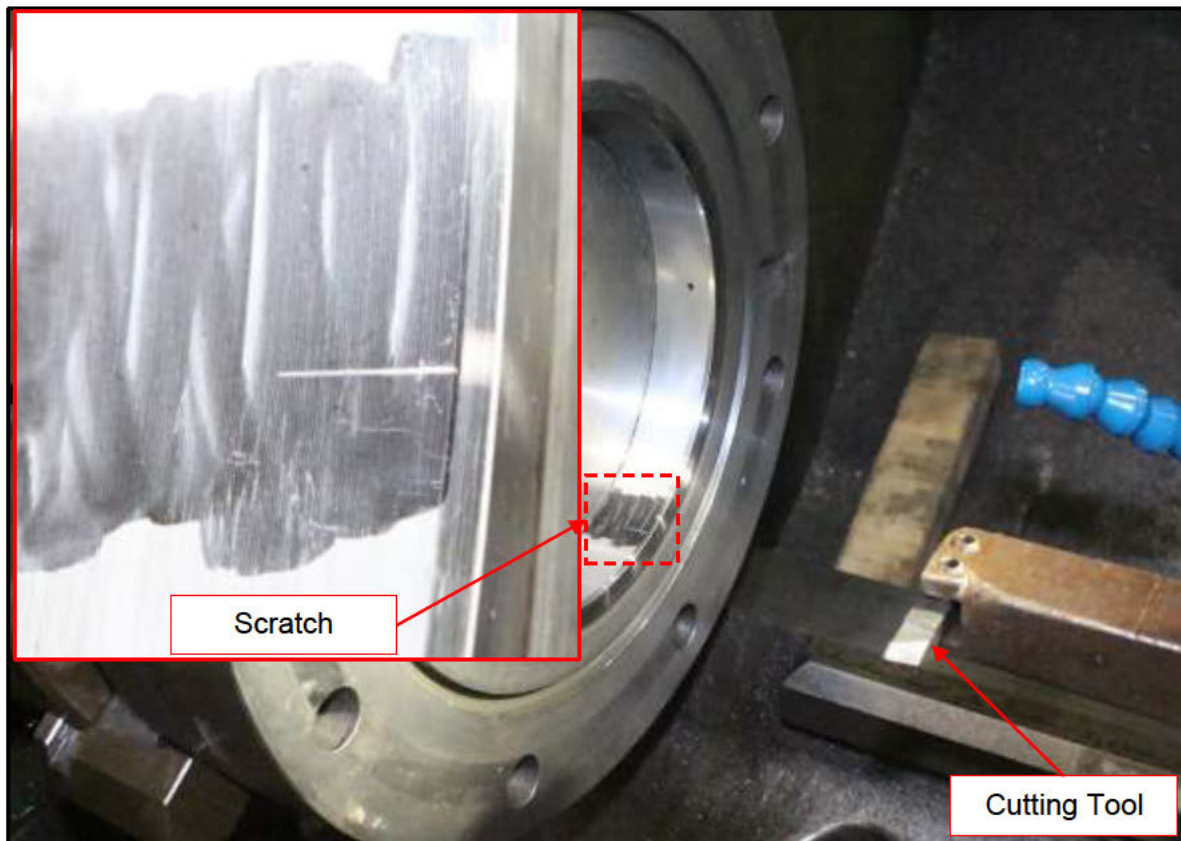


Figure 11: Damage Level 1



Figure 12: Damage Level 3



Figure 13: Damage Level 4



Figure 14: Damage Level 5



Figure 15: Damage Level 6



Figure 16: Damage Level 7

6.2.4 Test Set-Up

To test the sealant compounds, the test gas pack was connected to a control panel so that pressure could be introduced to the test plates incrementally in a controlled manner. From the control panel, a hose was connected to the test plate assembly via Snap-On fittings and into the plate inlet port. A bubble pipe was fitted to the Tell-Tale port which was where the hydrogen detector probe was placed to quantify the leakage. Prior to testing the sealant compounds, the sealant would be injected into the assembly via the injector fittings using a foot pump. The sealant was typically charged to around 1000psig. The final assembled test plates can be seen in Figure 17, whereas the test set-up from gas pack to test rig can be seen in Figure 18 and Figure 19.

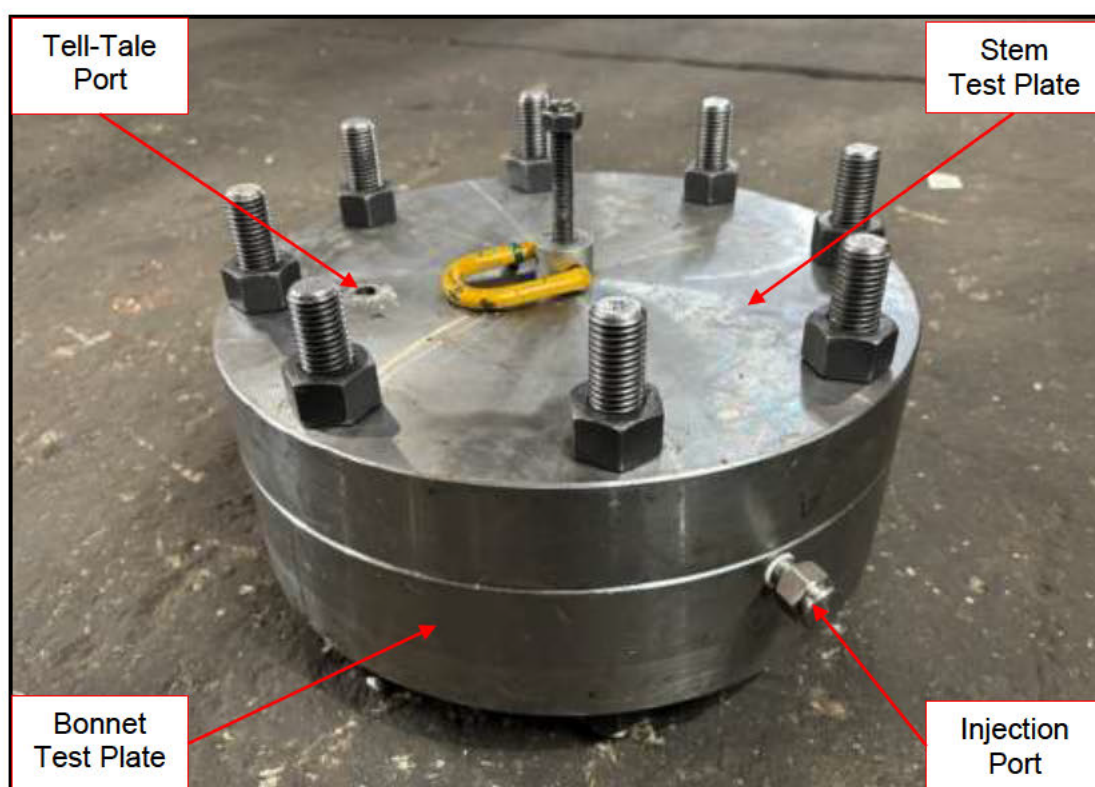


Figure 17: Test Rig Assembly

This test set-up showcases an accurate representation of a stem to bonnet sealing arrangement complete with sealant injection facilities, typical of a [REDACTED] valve design which are commonplace in NGT's NTS. Given O-Rings are commonly employed as the main seat insert throughout [REDACTED] valve range, this set-up could also be considered to represent the seat to ball interface, as an O-Ring is in contact with a solid metal face which may have material loss damage, requiring injection grease to seal the resultant leakage. However, as the 'bonnet' face is perfectly perpendicular to the O-Ring, there is scope to create a set-up that more aligns with a seat to ball interface.

As detailed in the Hydrogen Impact on NTS Valve project (NIA_NGT0227 // Score Job Number 665997 EDC [2]), there is an ex-service NTS valve in Score which has been repurposed to be hydrogen ready, and could potentially be employed to carry out further grease injection trials. As these tests would be conducted on a valve similar to NGT's valve population, this will further enhance Score and NGT's knowledge on how sealant greases will react to hydrogen.

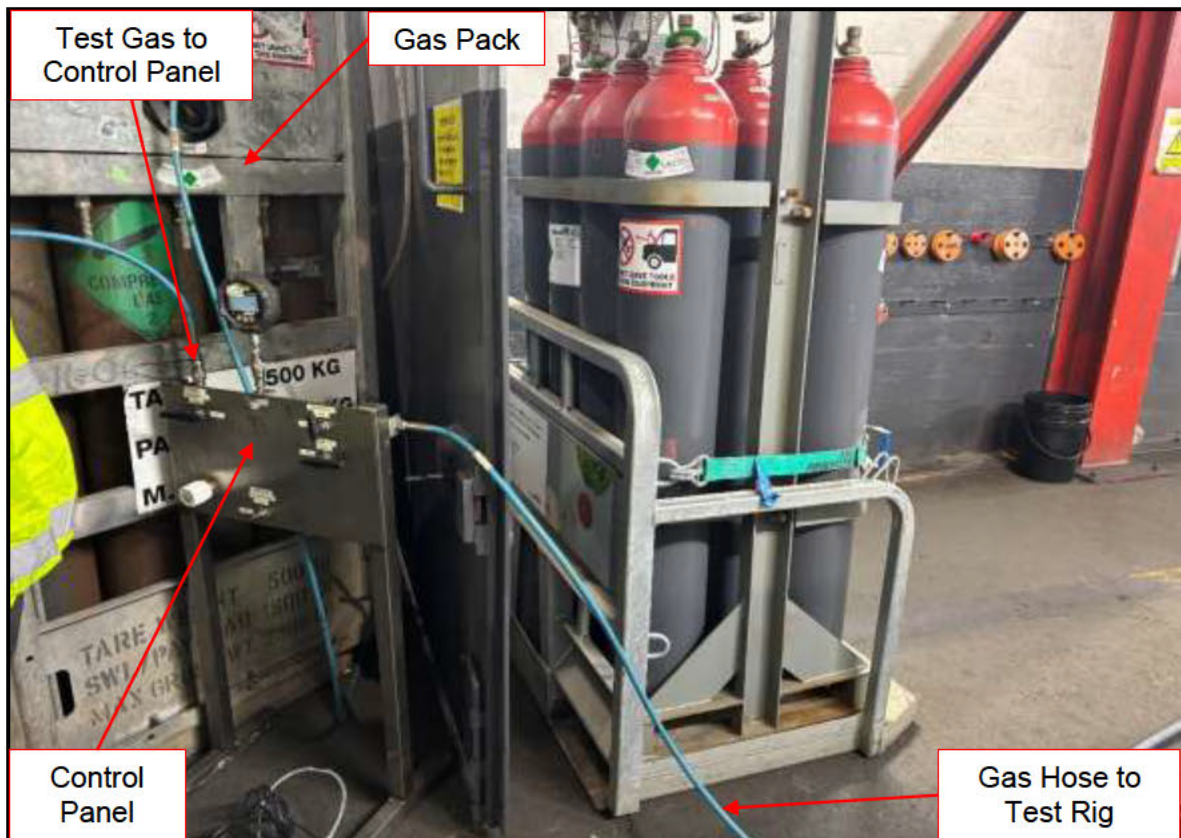


Figure 18: Test Set-Up (1)

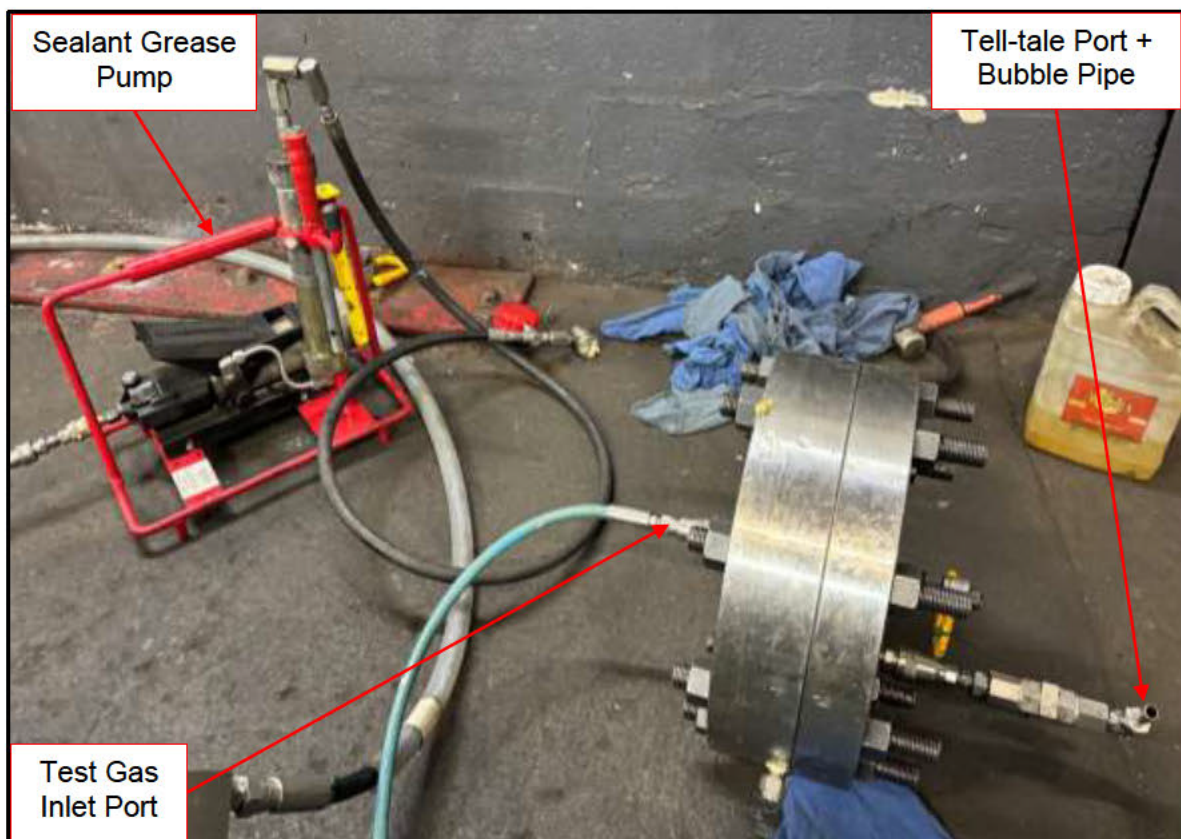


Figure 19: Test Set-Up (2)

6.2.5 Test Parameters

Listed below are the basic test parameters for the sealant injection trial testing:

Pressure:	113 barg (in 25 barg intervals)
Temperature:	Ambient
Test Gas:	Forming Gas (5% hydrogen / 95% nitrogen mix)
Sealant Compounds:	
Sealant Settling Time:	5 minutes (charged to 1000psi)
Pressure Hold Time:	5 minutes (per interval)
Hydrogen Detector:	Inficon Extrima
Calibration Intervals:	Prior to each sealant compound test

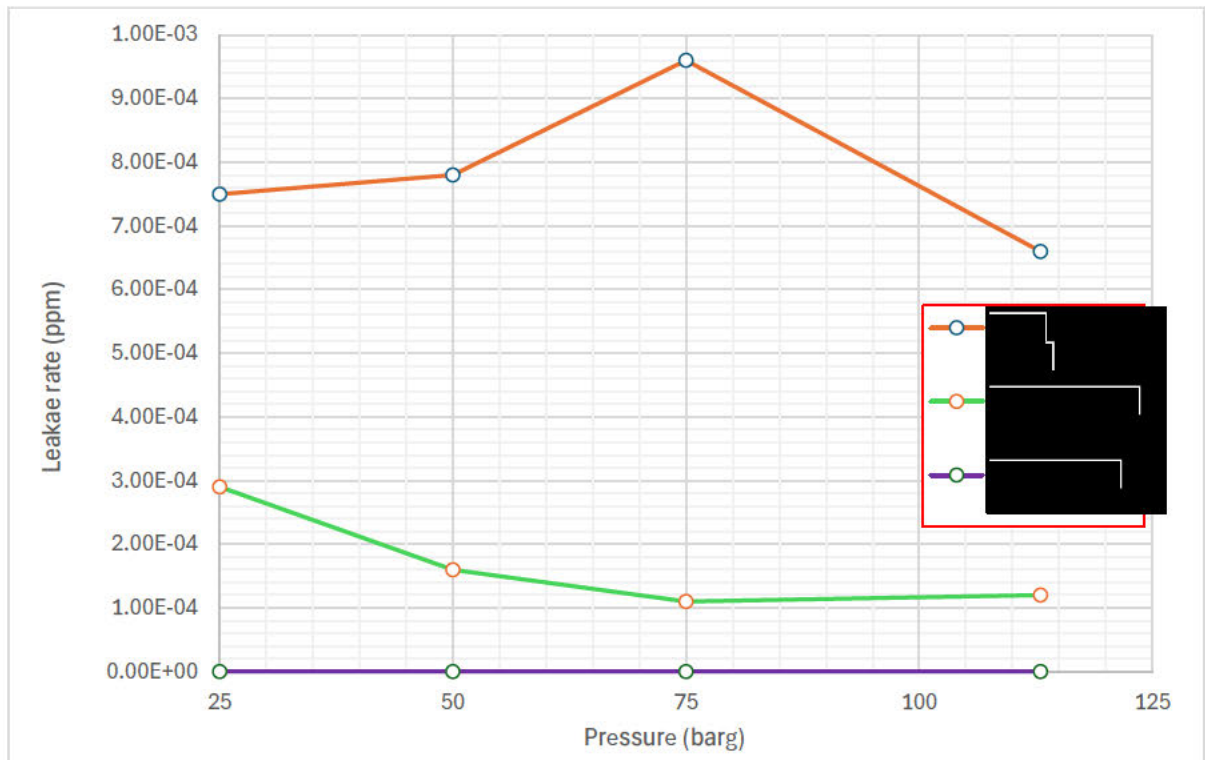
6.2.6 Inficon Extrima Hydrogen Leak Detector

The hydrogen leak detector used during pressure testing with forming gas was the Extrima hydrogen detector manufactured by Inficon. The detector is not a mass spectrometer as it does not have a vacuum to suck the trace gas into its sensor but rather depends on a flow to transport the hydrogen atoms into the probe. Once the gas enters the probe, any hydrogen atoms will diffuse into a metal plate (or gate) within the probe, which is sensitive to hydrogen only. Once diffused, the hydrogen atoms become hydrogen ions (protons) which change the gate's surface potential, essentially creating an electrical flow which is converted into a concentration (ppm) or flow (mbarL/s) reading. The detector is far smaller than a mass spectrometer and has an attachment strap so can be transportable around site, making it ideal for tracing and detecting leaks on-site.

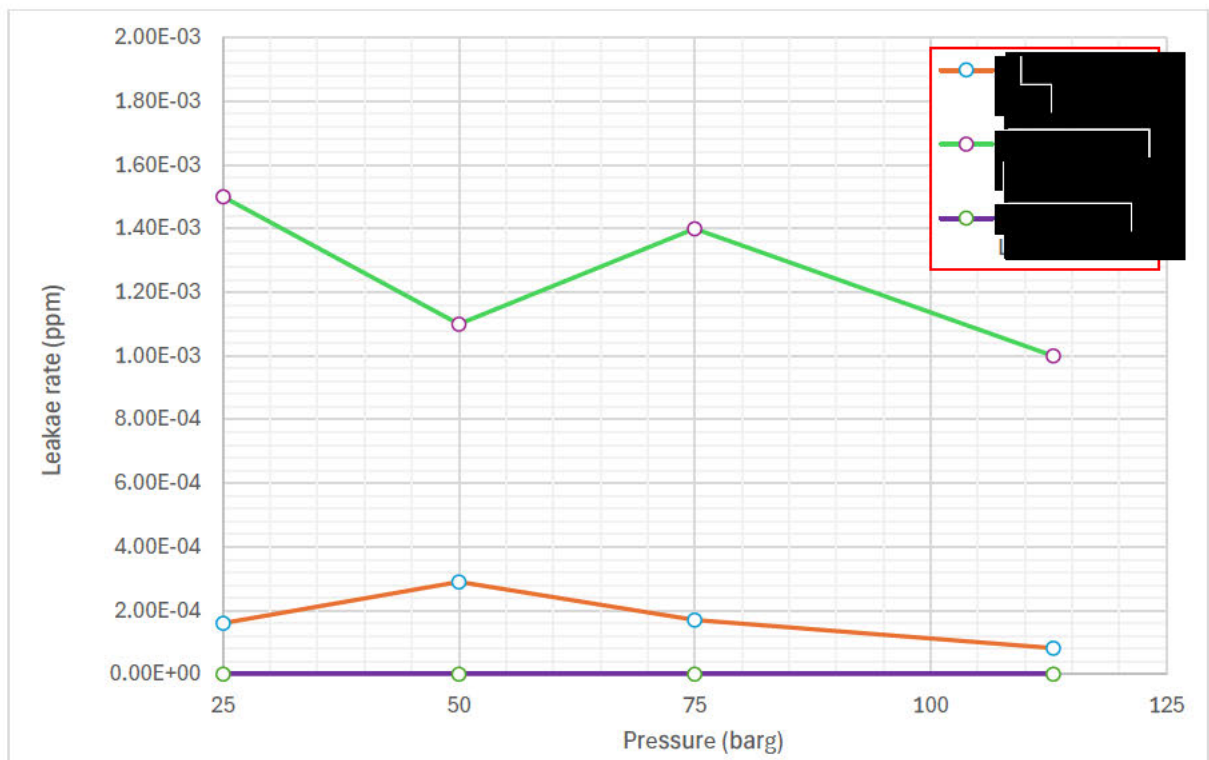
It is Ex rated meaning it is intrinsically safe, particularly important when detecting a gas as unstable as hydrogen. The device can and should be calibrated regularly with a calibration gas of the same composition as the subject gas to be detected, which Score have sourced from Inficon's preferred gas supplier, Buse. To calibrate the detector, a calibration fitting with a known "leak rate" is attached to the outlet of the calibration bottle regulator, allowing the trace gas to flow through the fitting at a fixed rate. The fitting has been developed by Inficon and is accompanied by a calibration certificate, stating the fixed flowrate at which the fitting will allow trace gas to flow through, which is the value to be inputted to the Inficon Extrima detector to calibrate. The manual for this equipment can be found in Appendix H.

6.2.7 Test Results

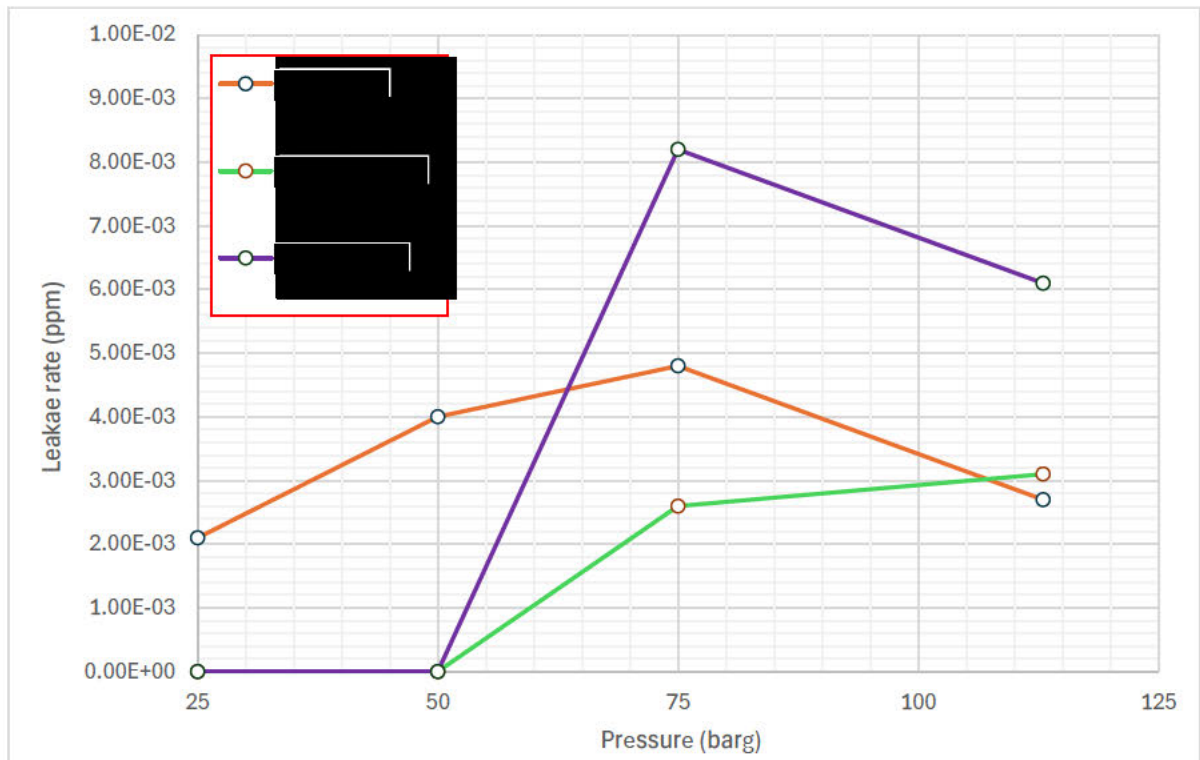
Graph 2 to Graph 5 below show a visual comparison of the test results for all 3 compounds across each damage level, whereas the individual readings for each test can be found in Table 8 to Table 11 in Appendix J. It should be noted that as the measured baseline leakage for damage levels 1 to 3 were 0, it was deemed unnecessary to inject any sealant compound and re-test, as there was no baseline leakage measurement to compare to, hence no sealant injection trials were carried out at these damage levels. Also, the baseline leakage rate (i.e. leakage without sealant) was measured to be the same for damage levels 4 – 7 as the hydrogen Leak Detector appeared to 'max out' at these values, meaning the actual leakage may be higher than displayed on the readout.



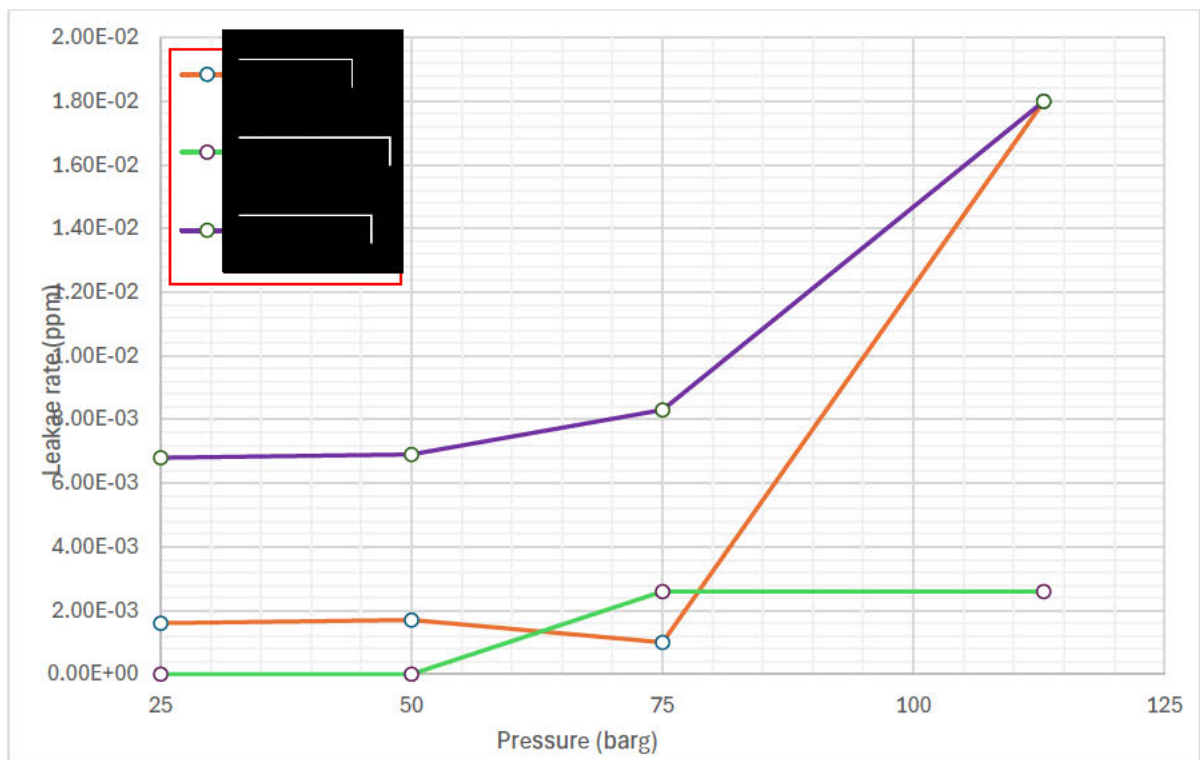
Graph 2: Damage Level 4 Results



Graph 3: Damage Level 5 Results



Graph 4: Damage Level 6 Results



Graph 5: Damage Level 7 Results

6.2.8 Discussion

6.2.8.1 General

Overall, each sealant compound did manage to offer a reduction in leakage measured by the Extrima across all damage levels to some degree, however not one compound could be identified as a clear “best option” when compared to each other. Each compound has their own advantages and disadvantages over each other, which shall be discussed below and are also summarised in Table 7. Leakage readings may show large variance upon first glance; however, it should be considered the small scale that these readings are being taken at. For example, the smallest and largest leakage readings for [REDACTED] at damage level 4 are, respectively, 6.6×10^{-4} ppm and 9.6×10^{-4} ppm. The largest value is over 45% higher than the lowest, however this equates to an actual change of a mere 0.0003 ppm. Therefore, when considering results, more emphasis should be placed on the leakage result order of magnitude, as this is a clear indication of performance. Logarithmic by nature, the variance in results at higher order of magnitudes ($\times 10^{-3}$ and higher) carry a greater weight than they do at the lower order of magnitudes ($\times 10^{-4}$ and less).

[REDACTED]

The performance of [REDACTED] can be described as consistent, but not the best performer in any bracket, as can be seen from Graph 2 to Graph 5. Except for damage level 4, [REDACTED] was the 2nd best performer, where leakage was reduced to similar values throughout testing. This trend is not true however for the full test pressure on the deepest notch test (level 7 damage), as can be seen from Graph 5. Leakage rates spiked to the maximum readout value on the Extrima for this trace gas, where the pressure gauge was dropping rapidly, hence the sealant grease offered no means of a sealing barrier at max test pressure. This was to be expected as the notch was deeper than any corrosion damage would be expected to reach, hence it can be concluded that [REDACTED] would likely suffice for sealant injection as a leakage mitigation method against hydrogen at typically expected corrosion damage levels. Given a sealing barrier was provided at max damage level up to 75 barg, it appears [REDACTED] has some offering of extreme damage sealing protection, but reliable sealing performance cannot be guaranteed at this level of damage.

[REDACTED] was sourced in stick [REDACTED], which is the most common size and would be applied throughout a wide range of activities across Score Group's portfolio. It is a tested and proven compound for the Oil and Gas industry, providing great leakage reduction for isolation valves, namely ball valves, on both liquid and gas applications. The stick format was easy to load into the pump chamber and easy to charge through the hose and into the test rig. [REDACTED], or as thin or sticky as [REDACTED] sits in the middle of these two compounds with regards to its viscosity and consistency, resulting in an easy to inject and easy to flush sealant grease. Upon disassembly of the test rig after the maximum damage level test with [REDACTED], Figure 20 & Figure 21 shows that the compound spreads out sparsely and inconsistently over the entire plate face. It is proposed that this occurs due to the compound being fairly viscous, [REDACTED] which shall be discussed in the following section.

Finally, given Score are an approved distributor of [REDACTED], Score can easily source this sealant compound should NGT decide to select this grease as their preferred hydrogen leakage mitigation sealant injection compound.



Figure 20: [REDACTED] Remains in Test Plate (1)



Figure 21: [REDACTED] Remains in Test Plate (2)

Results were superior to [REDACTED] for damage level 4 at around 1×10^{-4} ppm (see Graph 2), but performance did drop off during damage level 5 testing by a full order of magnitude, yielding leakage results around 1×10^{-3} ppm - 10x higher than at level 4 (see Graph 3). It should be noted however that these results are still offering some form of sealing barrier as the pressure gauge was holding steady, showing that measured leakage by the Extrima does not necessarily equate to a pressure drop off.

Technicians stated that the grease was the most difficult to handle as the consistency was extremely 'sticky'. Its stickiness resulted in the grease being challenging to remove from its packaging and into the pump chamber, sticking to most tools used to scrape the grease into the piston chamber. Similar challenges were encountered when attempting to clean out the pump chamber after [REDACTED] tests were complete, meaning there was remanence of the grease throughout the pump and hose. Also, it was noted that many air bubbles were being formed when compressing the grease in the pump chamber using the piston rod, meaning it was harder to charge when pumping. The other compounds retained their stick form better, resulting in an easier loading process.

When removing the test plates from each other, the stickiness of the compound can clearly be shown in Figure 22 and Figure 23 from the raised ridges where the grease was clinging to both plates, which was not evident for [REDACTED]. The grease began to perform better at the higher damage levels, showing 0 leakage up to 75 barg at damage levels 6 and 7 (see Graph 4 and Graph 5). When the compound did show leakage for damage levels 6 & 7 at 75 barg and above, they were comparable to [REDACTED] leakage readings at level 5 (approx. 3×10^{-3} ppm), and were also superior to [REDACTED] leakage readings for level 6 & 7.

Upon closer inspection of the grease, it appears that [REDACTED] contains small pieces of PTFE flakes throughout (see Figure 24). It is thought that these flakes could not fit into the machined notch at damage levels 4 & 5 but had more success in the deeper score depths from damage levels 6 & 7. The grease itself is less viscous than [REDACTED] and is theorised to be too thin to provide a suitable barrier by itself but instead appears to act as an ideal carrier for the flakes into the larger, deeper scores. Hence, when the score was too small for the PTFE flakes to enter and be relied upon for a seal, its performance was low but improved when the notch was large enough for the PTFE to coagulate and provide a solid barrier.

When inspecting the plates upon disassembly after level 7 damage testing, remanence of grease that was once formed into the machined notch could clearly be seen, resembling a solid column (see Figure 22 & Figure 23), which is not the case for other greases. This supports the premise that the PTFE flakes help to form a strong, solid barrier in these larger notches which the other greases cannot do, resulting in a sealant compound which is more tailored for larger defects.

It can be concluded that [REDACTED] would be a great sealant injection solution to mitigate hydrogen leakage for NGT's NTS valves. Although its performance is not optimal at the typically expected corrosion damage levels (4 and 5), it does still offer a sealing barrier which only improves as the damage worsens, resulting in a solution that can be applied to valves with high leakage rates. Finally, given Score have a distribution agreement with [REDACTED], Score can easily source this sealant compound should NGT decide to select this grease as their preferred hydrogen leakage mitigation sealant injection compound.

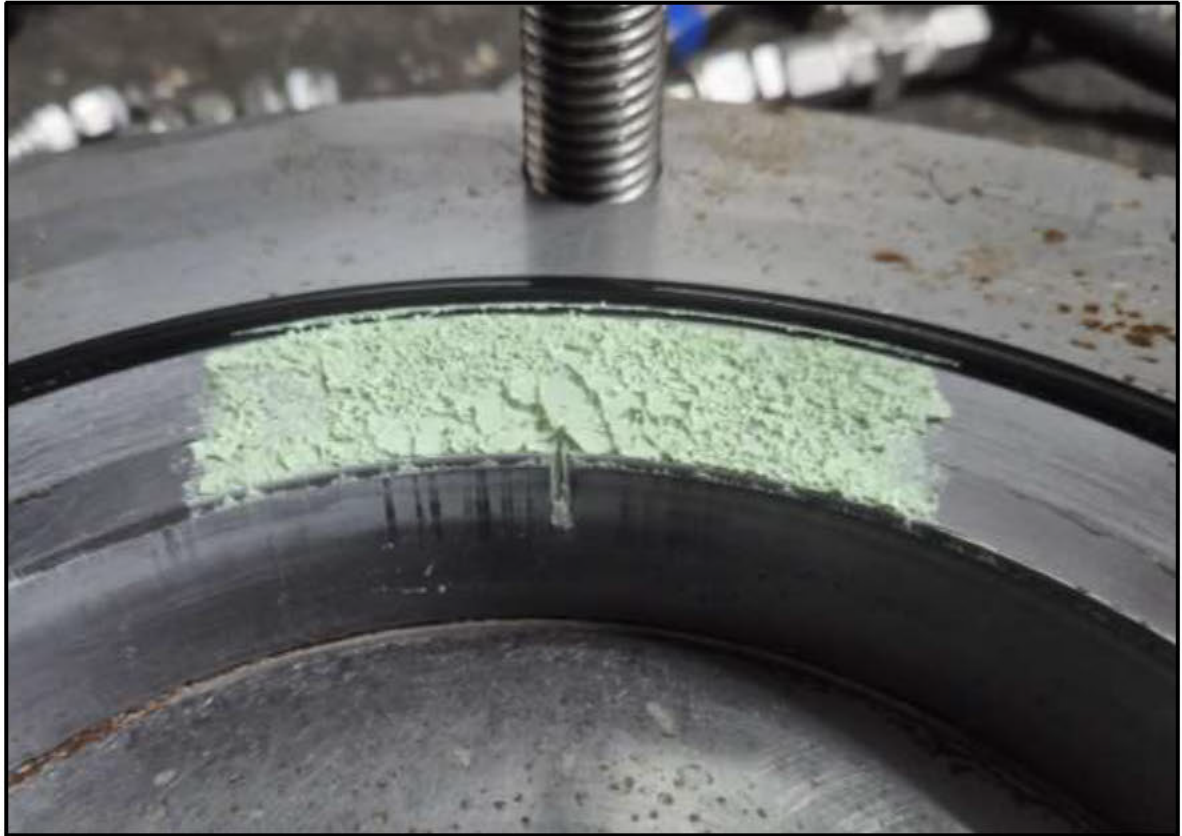


Figure 22: [REDACTED] (1)

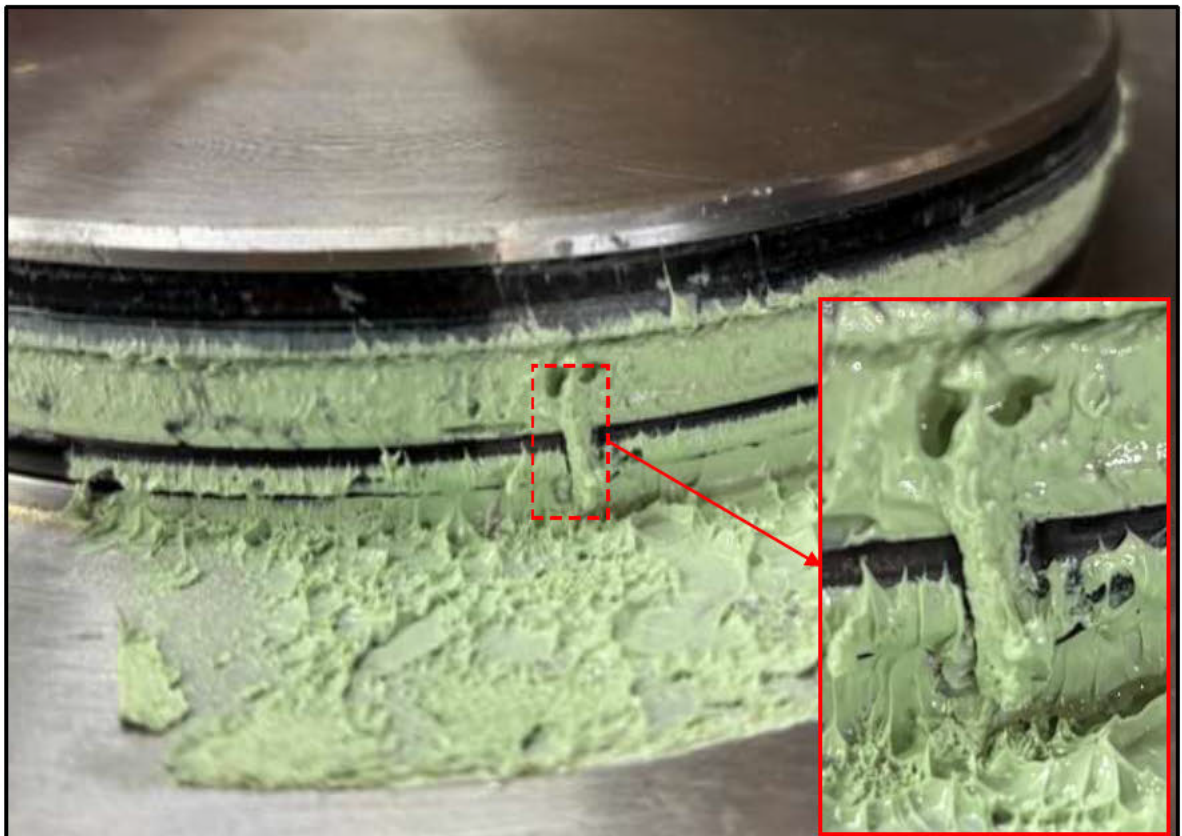


Figure 23: [REDACTED]

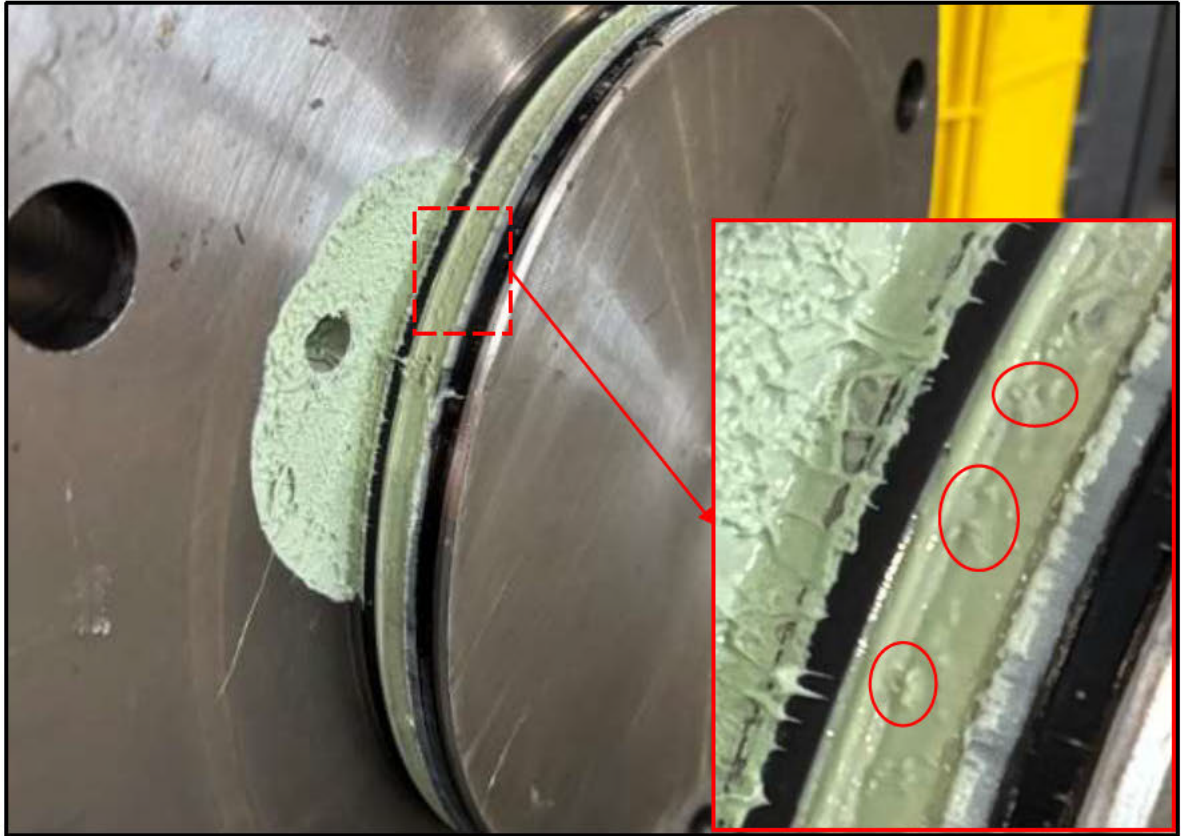


Figure 24: [REDACTED]

██████████ was easily the best performing compound at intermediate damage levels (level 4 and 5), as can be seen in Graph 2 and Graph 3, boasting 0 leakage throughout all tests. Technicians noted whilst loading the sealant pump that the consistency was the most dense and viscous of all 3 compounds, hence it was thought that the 0 leakage results were attributed to its physical properties. ██████████, this compound was easy to handle, easy to load and, despite its thicker consistency, easy to inject to the test rig. The 0-leakage trend did end during level 6 damage however, as hydrogen leakage was detected by the Extrima after 50 barg pressure application (see Graph 4), albeit the pressure gauge showed minimal pressure drop off, meaning a barrier was still formed.

Despite this, Graph 4 and Graph 5 shows that ██████████ became the worst performing compound from all 3 at the higher damage levels (6 and 7), giving way to a pressure drop off leakage at the same point as ██████████ did, which was above 50 barg at the maximum damage level. Again, similar to ██████████, the remnants of the grease upon disassembly of the test rig after the maximum damage test showed a sparse and inconsistent spread across the face (Figure 25 and Figure 26). Given both compounds which exhibited this phenomenon was subject to a pressure drop off leakage at test pressure for the maximum damage level (██████████), it can be concluded that this is not a desirable effect.

██████████ would incur, hence Score can recommend this sealant for general hydrogen leakage mitigation application. When deeper scores are present however, as is the case ██████████, the performance does drop off. ██████████ does have some offering of extreme damage sealing protection, but reliable sealing performance cannot be guaranteed. It appears ██████████ have a directly opposite performance trend when subject to the same test conditions, meaning where one sealant fails, the other succeeds, so ██████████ could be employed where ██████████ begins to fail at these higher damage levels. Finally, unlike ██████████ no distribution agreement is in place ██████████. Score can therefore not guarantee supply of this compound should NGT decide to select this grease as their preferred hydrogen leakage mitigation sealant injection compound.



Figure 25: [REDACTED]

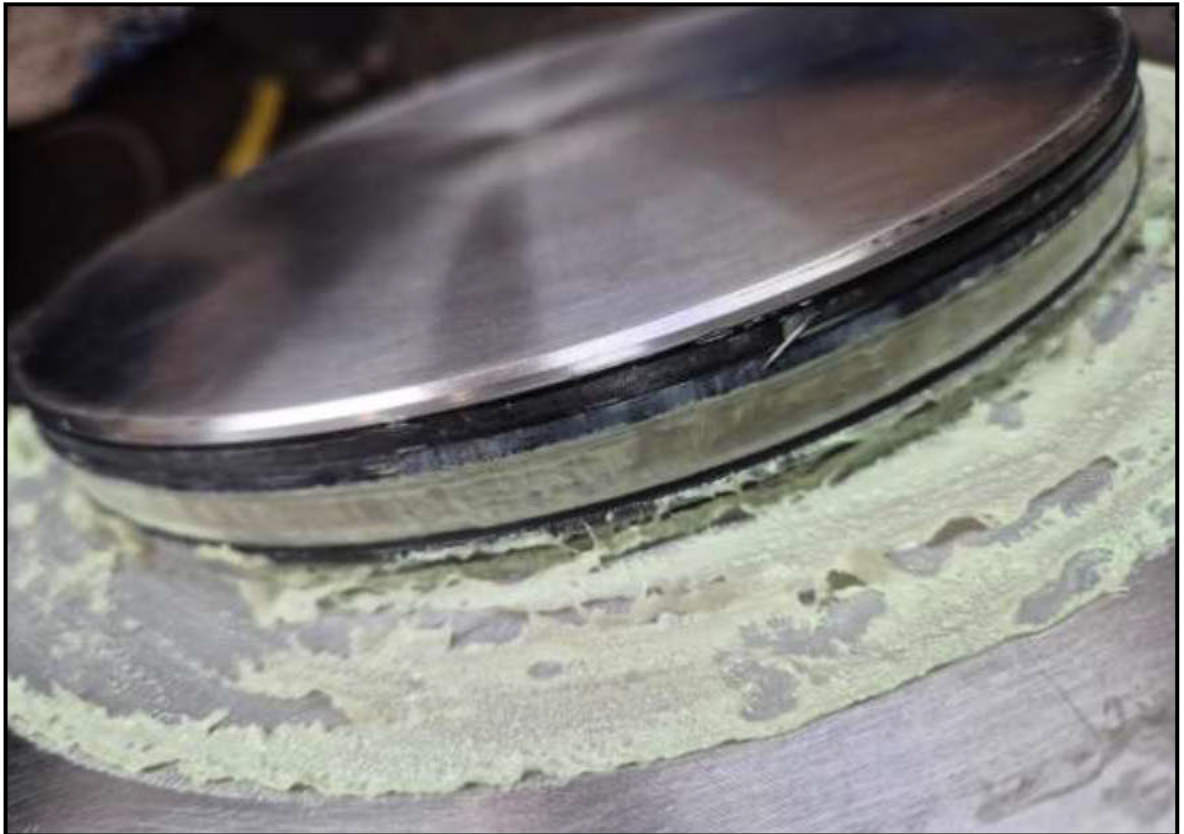


Figure 26: [REDACTED]

7.0 WP4 – IN-SERVICE ASSESSMENTS

7.1 Oils In-Service Assessment Plan

It is proposed by Score that NGT [REDACTED] where possible in their NTS upon transition to hydrogen, as it displayed no change in performance when exposed to hydrogen across all tests conducted by [REDACTED]. All key variables (such as water separation, air release, 4-ball wear, viscosity and density) showed no reportable changes when comparing the hydrogen conditioned oil sample to the control sample, verifying the oil's indifference to being exposed to hydrogen, thereby proving its compatibility.

7.1.2 [REDACTED] Application Expansion

Given some oils are more tailored to certain equipment and components than others (depending on variables such as oil density or viscosity levels requirements), Score cannot comment on the effectiveness of [REDACTED] across all of NGT's rotating equipment. However, it can be confirmed that no performance drop would be expected upon the introduction of hydrogen where the oil is currently being utilised. Both other oils showed signs of property changes upon hydrogen exposure; therefore it may be beneficial to investigate the wholesale application of [REDACTED] where appropriate.

7.1.2.1 Rotating Equipment Testing

It may be the case that the subject oils have been chosen for certain applications or components within the NTS based on physical parameters, such as its kinematic viscosity levels for example. Certain viscosity levels may provide optimal protection and lubrication in specific equipment, thereby excluding the consideration of utilising the other oils. The below list shows the kinematic viscosity of the 3-off tested oils as per [REDACTED] results.

[REDACTED]
[REDACTED]
[REDACTED]

This means that, for example, if a certain piece of equipment requires an oil with a kinematic viscosity of around 33 cSt for optimal operation (i.e. [REDACTED]), an hydrogen compatible oil will need to be found with similar physical properties to ensure safe operation of the equipment. Given the hydrogen proven [REDACTED] may not be viscous enough for that equipment or application, it cannot be proposed to be utilised without confirmation of equipment compatibility testing.

Moving forward, trial testing could be conducted on equipment that does not currently use [REDACTED] as its lubricant to investigate the possibility of adopting this as a 'go-to' lubricant across the entire NTS. By running tests on a select number of rotating equipment/components, both on its current lubricating oil and with [REDACTED], a comparative study can be completed. This will help NGT's understanding of where [REDACTED] can and cannot be used throughout their rotating equipment population within the NTS.

7.1.3 [REDACTED] Concerns

[REDACTED] both exhibited signs of degradation upon hydrogen exposure, the former more so than the latter. On this basis, Score cannot recommend these oils for use in NGT's NTS upon transition to hydrogen until further research has been carried out on these oils to alleviate concerns; or to further confirm its unsuitability. It is expected that [REDACTED] may be in a better position to be utilised than [REDACTED] superior performance in the 4-ball wear test, but again cannot be conclusively stated at this time.

[REDACTED]

Further testing could include a comparison of the performance of select rotating equipment with unconditioned oil and its hydrogen conditioned oil counterpart. Selecting equipment that already uses [REDACTED] range would be imperative as the unconditioned oil tests would be an accurate baseline measurement of the equipment's actual performance in line. Comparing these results to that of the equipment's performance with the hydrogen conditioned oil provides a physical test that will highlight the significance of the property changes shown in the [REDACTED] test report. It may be the case that the property changes reported during lab testing has a minimal impact on the equipment's actual performance, giving a more pragmatic testing approach. However, it should be noted that the 4-ball wear test does fulfil these criteria in some regards, therefore on that basis, only testing of [REDACTED] would be recommended given [REDACTED] poor 4-ball wear performance.

7.1.3.2 Further Other Oils Testing

As discussed above, it may be the case that the most resilient oil to hydrogen ([REDACTED]) may not be compatible with some of NGT's rotating equipment. Should this be the case, as an alternative to testing rotating equipment, further testing on a different suite of oils can be carried out. This could be done in a similar way as discussed in this report to find an oil with comparable hydrogen resilience [REDACTED] but with suitable physical characteristics for its application.

NGT could share their decision-making process with Score regarding which rotating equipment [REDACTED] (or other oil compounds), to which Score can then conduct further testing on a range of oils that have similar physical properties with the view of replacing [REDACTED] with an oil which has similar hydrogen resistance as [REDACTED]. This can be done on any oil which NGT currently utilise, [REDACTED] was used as an example in this case given its poor performance during [REDACTED].

7.1.4 OEM Responses & Procurement List

[REDACTED]

7.2 Greases In-Service Assessment Plan

7.2.1 Forming Gas Allowable Leakage Guidance

As per Table M.3 from API 6D Annex M Section M.8.4.3.3 [24], the allowable leakage when conducting FATs on valves using forming gas depends on the component, the geometry of that component and the emission tightness class (see Figure 27). For the test set-up detailed in this report, the relevant sealing diameter would be 7.718in (as per Figure 6), equating to 196mm. The allowable leakage for this set-up was calculated and shown in Table 6 below, accompanied by the relevant sealant grease and damage level which met this allowable leakage.

Table M.3—Fugitive Emission Test Acceptance Criteria—Forming Gas		
Emission Tightness Class	Allowable leakage rate stem seal ^{a, c}	Allowable leakage rate body seal ^{b, c}
	mbar-l/s per mm diameter	mbar-l/s per mm diameter
A ^d	$\leq 5.93 \times 10^{-6}$	$\leq 5.93 \times 10^{-9}$
B ^e	$\leq 5.93 \times 10^{-7}$	$\leq 5.93 \times 10^{-8}$
FOOTNOTES ^a For stem seals; diameter shall be the stem diameter in millimeters at the point of measurement. ^b For body-to-bonnet or body-to-cover seals; diameter shall be the outer diameter of the gasket in millimeters at the point of measurement. For non-circular gaskets, the equivalent diameter shall be taken as the perimeter divided by (pi). ^c To be measured with forming gas tracer gas in mbar-l/s per mm diameter. ^d Due to the constraints of the sniffer technique, for stem seal diameters equal to or smaller than 34 mm, the maximum leakage shall be 2.1×10^{-6} mbar-l/s, and for body seal diameters equal or smaller than 340 mm, the maximum leakage shall be 2.1×10^{-6} mbar-l/s. ^e Due to the constraints of the sniffer technique, for stem seal diameters equal or smaller than 4 mm, the maximum leakage shall be 2.4×10^{-6} mbar-l/s, and for body seal diameters equal or smaller than 40 mm, the maximum leakage shall be 2.1×10^{-6} mbar-l/s.		

Figure 27: API 6D Table M.3 - Allowable Forming Gas Leakage

Calculated Allowable Forming Gas Leakage			
Leakage Class		Stem	Body Seal
A		1.16×10^{-5} (mbar. L/s)	1.16×10^{-6} (mbar. L/s)
B		1.16×10^{-4} (mbar. L/s)	1.16×10^{-5} (mbar. L/s)
Sealant Greases Meeting Allowable Leakage			
■	██████████	-	-
	██████████	Levels 6* & 7*	Levels 6* & 7*
	██████████	Levels 4 & 5 Level 6*	Level 4 Level 5** Level 6*
■	██████████	-	-
	██████████	Level 4 Levels 6* & 7*	Level 6* & 7*
	██████████	Levels 4 & 5 Level 6*	Levels 4 & 5 Level 6*
(*) up to 50 barg (**) up to 75 barg			

Table 6: Forming Gas Allowable Leakage for Subject Test Set-Up

7.2.2 Sealant Injection Grease Performance Overview

Overall, each sealant compound did manage to offer a reduction in leakage measured by the Inficon Extrima hydrogen detector across all damage levels to some degree. When compared to each other, there is not a single sealant grease which could be described as the “best option” as each have their own advantages and disadvantages over the other, which shall be discussed below and are summarised in Table 7. However, when compared to the allowable leakage rate stipulated in API 6D Annex M (see Section 7.2.1), [REDACTED] emerged as the best performer, followed closely by [REDACTED]

Sealant Compound	Advantages	Disadvantages
[REDACTED]	- Consistent Performance - Readily Available - Easy to Handle	- Sealing capabilities hindered at higher damage levels - Did not offer optimal performance at any damage level (see Table 6)
[REDACTED]	- Exceptional severe damage performance at lower pressures (see Table 6 and Graph 5) - Readily Available	- Difficult to handle - Poor performance at intermediate damage levels (see Graph 2 and Graph 3)
[REDACTED]	- Exceptional intermediate damage performance (see Table 6, Graph 2 and Graph 3) - Easy to Handle	- Poorer sealing capabilities at higher damage levels (see Graph 4 and Graph 5) - Not readily available

Table 7: Sealant Compound Comparison

7.2.3 Sealant Injection Grease Discussions

[REDACTED]

The performance of [REDACTED] can be described as consistent as it always provided a similar leakage measurement across most damage levels, not fluctuating in performance like the other two greases did. However, despite the consistency provided by the grease, the leakage measurements were consistently above the allowable leakage required to meet API 6D, therefore these tests would have been deemed a failure. On this basis, [REDACTED] is not recommended for wholesale application across NGT's NTS, albeit the grease would still be expected to help curb leakage to some level.

It can be concluded that [REDACTED] would be a suitable sealant injection solution to mitigate hydrogen leakage for NGT's NTS valves. Although its performance fluctuated throughout testing, it was found that it did meet API 6D Annex M allowable leakage levels for:

- Stem (Level 4 Damage - Leakage Class B)
- Stem (Level 6 & 7 Damage - Leakage Classes A + B, up to 50 barg)
- Body Seal (Level 6 & 7 Damage - Leakage Classes A + B, up to 50 barg)

This was the best performing grease at the higher damage levels, offering a solution that can be applied to valves with high leakage rates, which would be expected for valves in-situ without maintenance for a considerable time period. These deeper scores (damage level 6 [1mm] and level 7 [1.75mm]) would be representative of severe damage and is likely above and beyond what corrosion would inflict, more aligning with galling or severe material loss. This is a possible scenario for a portion of NGT's NTS valve population, meaning [REDACTED] could be employed to help reduce leakage for valves exhibiting high emissions. It is proposed that [REDACTED] offers better leakage mitigation at higher damage levels due to the PTFE flakes within the grease. It is theorised that these flakes could not fit into the machined notch at damage levels 4 & 5 but had more success in the deeper score depths from damage levels 6 & 7. The grease itself is less viscous than [REDACTED] and is theorised to be too thin to provide a suitable barrier by itself but instead appears to act as an ideal carrier for the flakes into the larger, deeper scores. Finally, given Score have a distribution agreement with [REDACTED], Score can easily source this sealant compound should NGT decide to select this grease as their preferred hydrogen leakage mitigation sealant injection compound.

[REDACTED] was easily the best performing compound at intermediate damage levels (damage level 4 [0.25mm] and level 5 [0.50mm]), as can be seen in Graph 2 and Graph 3, boasting 0 leakage throughout most tests. These damage levels would be a fair representation of the damage that severe pitting corrosion could exhibit within NGT's valve population. The performance does drop off at higher damage levels, performing worse than [REDACTED] on the most part, but did still offer some leakage mitigation meeting API 6D Annex M across a wide range of levels, as per the below:

- Stem (Level 4 & 5 Damage - Leakage Class A + B)
- Stem (Level 6 Damage - Leakage Class A +B, up to 50 barg)
- Body Seal (Level 4 Damage - Leakage Classes A + B)
- Body Seal (Level 5 Damage – Leakage Class A, up to 75 barg)
- Body Seal (Level 5 Damage – Leakage Class B)
- Body Seal (Level 6 Damage - Leakage Classes A + B, up to 50 barg)

On this basis, it can be concluded that [REDACTED] would be a suitable sealant injection solution to mitigate hydrogen leakage for NGT's NTS valves.

7.2.4 Sealant Injection Grease Recommendations

Upon reviewing results, Score Engineering recommend a hybrid solution, implementing both [REDACTED] into NGT's maintenance schedule.

For standard, moderate leakages, [REDACTED] would be the best solution, as this looks to offer a sealing barrier pertaining to Leakage Class 'A' from API 6D Annex M for damage levels consistent with pitting corrosion damage.

Where excessive material loss damage and high leakages are present, it is proposed that [REDACTED] could be the optimal solution, as this offered 0 leakage at various pressures at the extreme damage levels during in-house testing.

7.2.5 Sealants OEM Responses

Score reached out to the following greases manufacturers to gain an insight on their testing and qualification regarding hydrogen readiness, submitting an OEM RFI to be filled out (see Appendix L).

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

[REDACTED]

API 622 'Low E' qualification for valve emission conformance, as shown in Appendix M.

[REDACTED]

[REDACTED]

8.0 DISTRIBUTION LIST

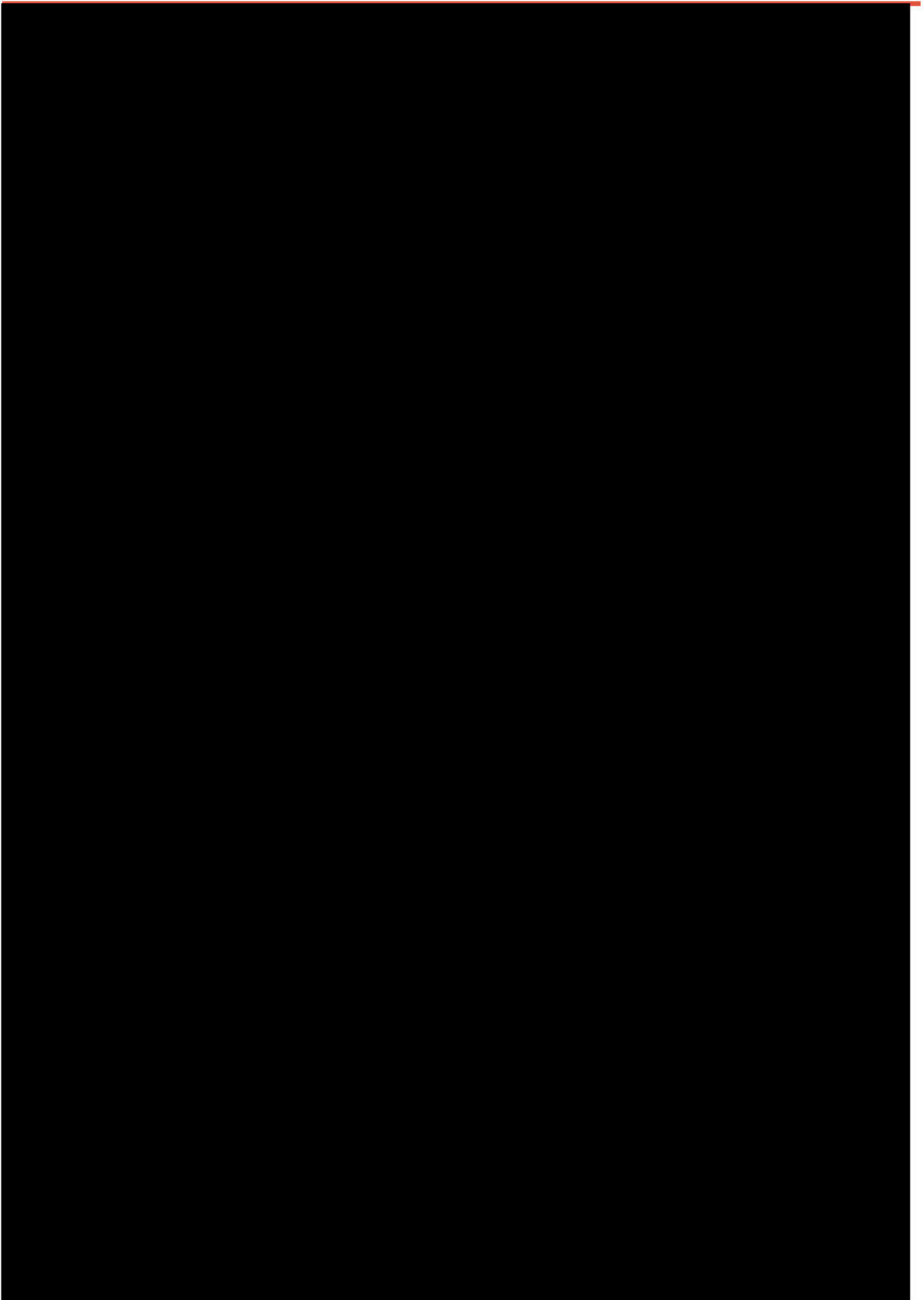
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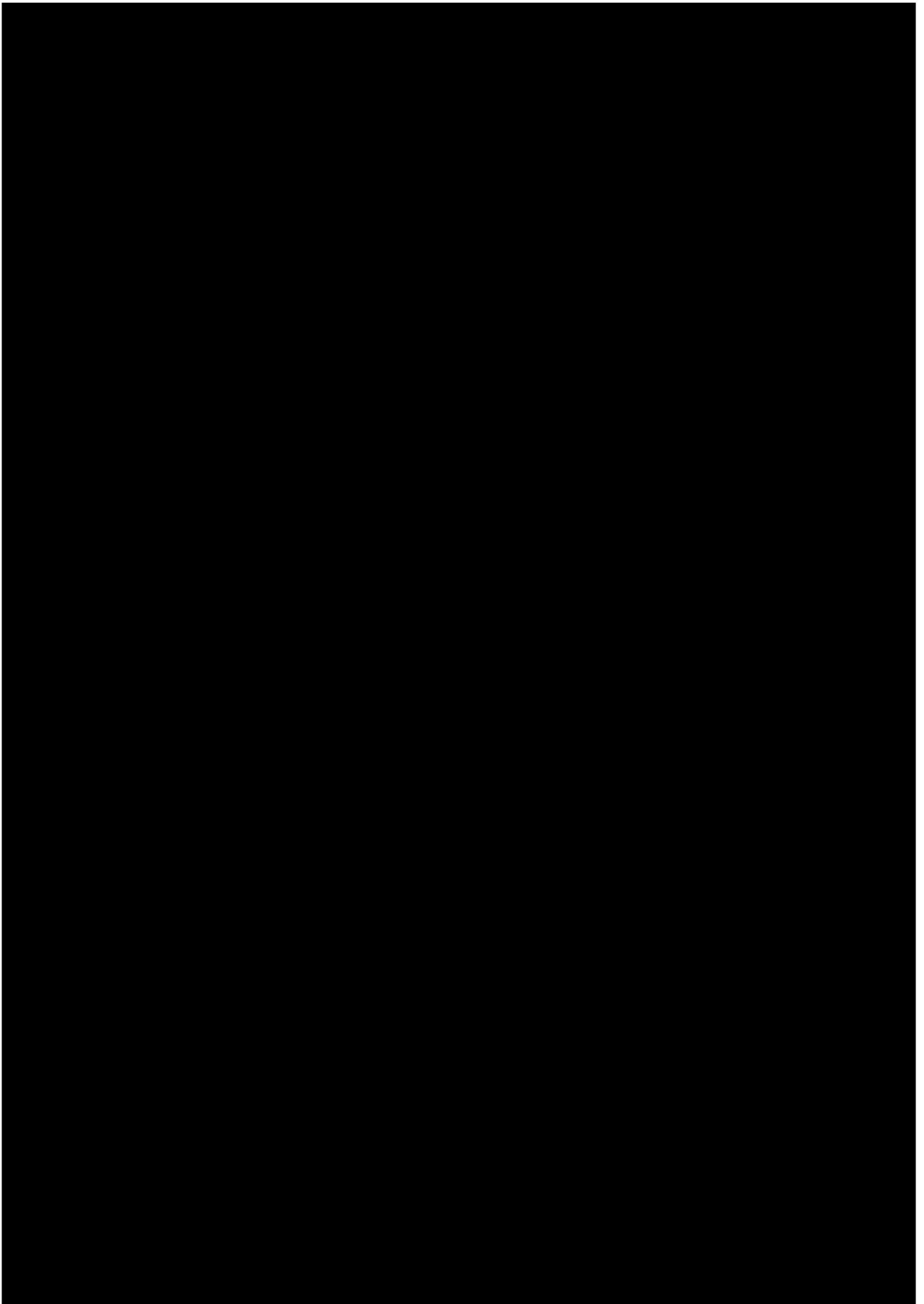
9.0 REFERENCES

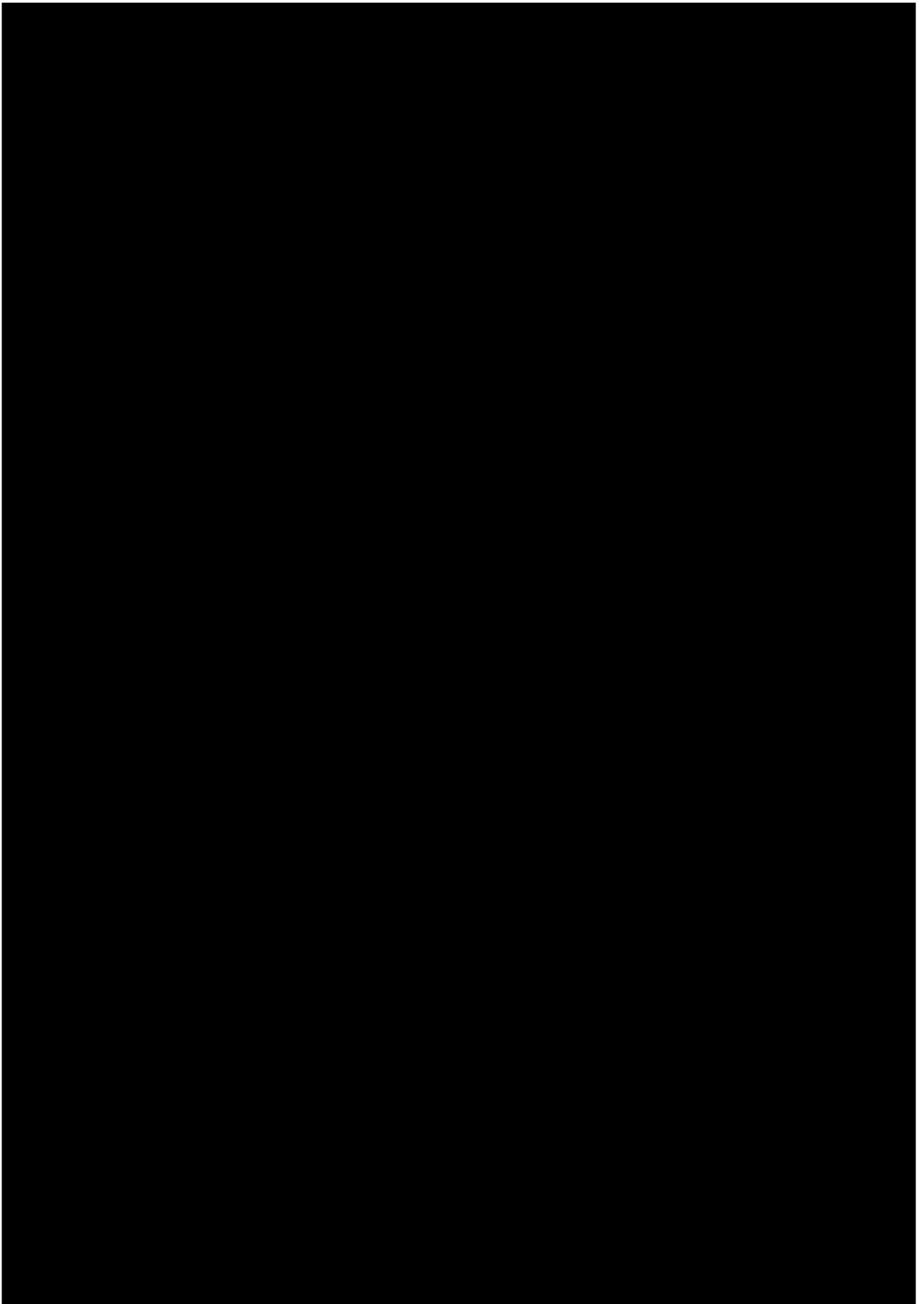
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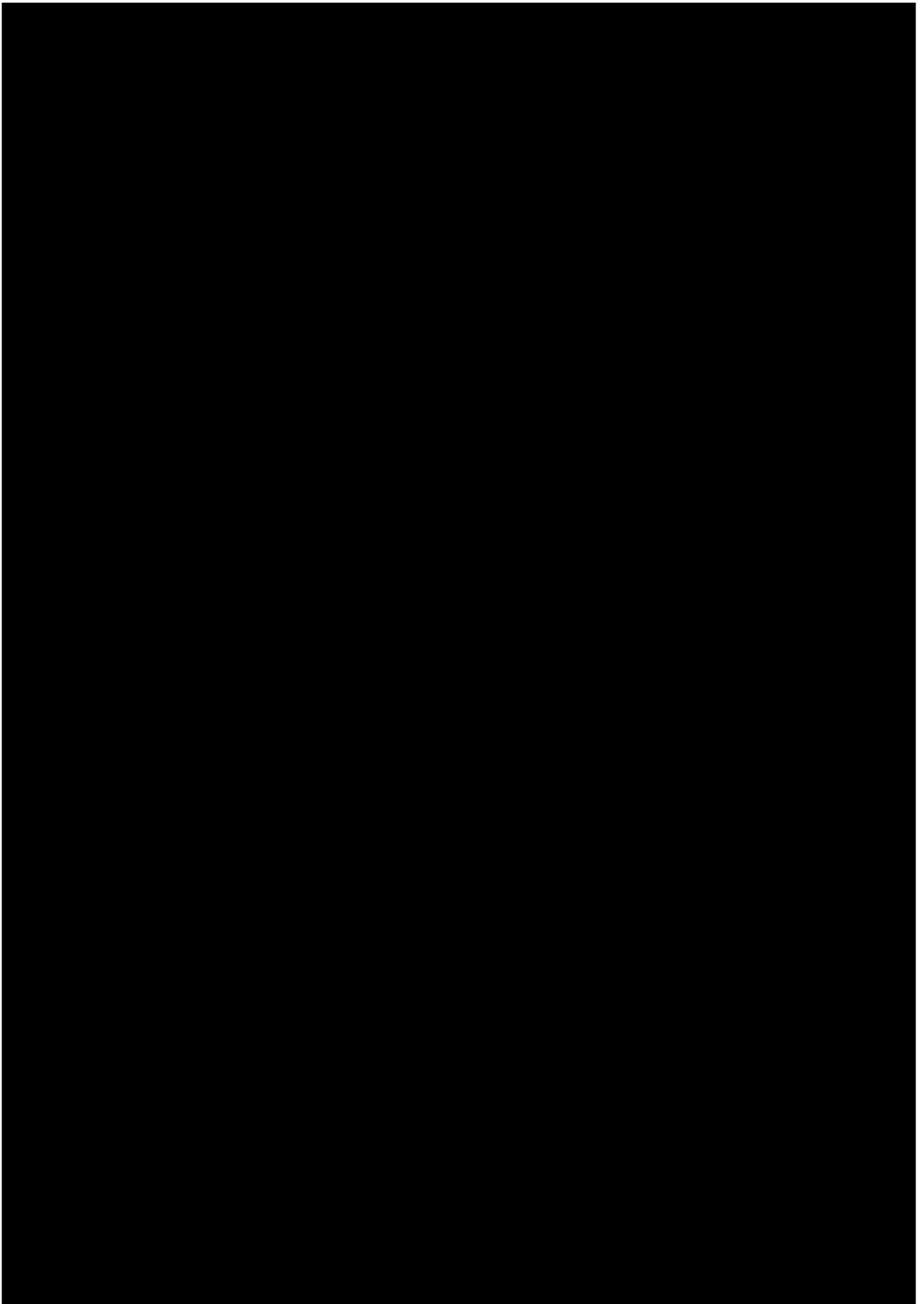
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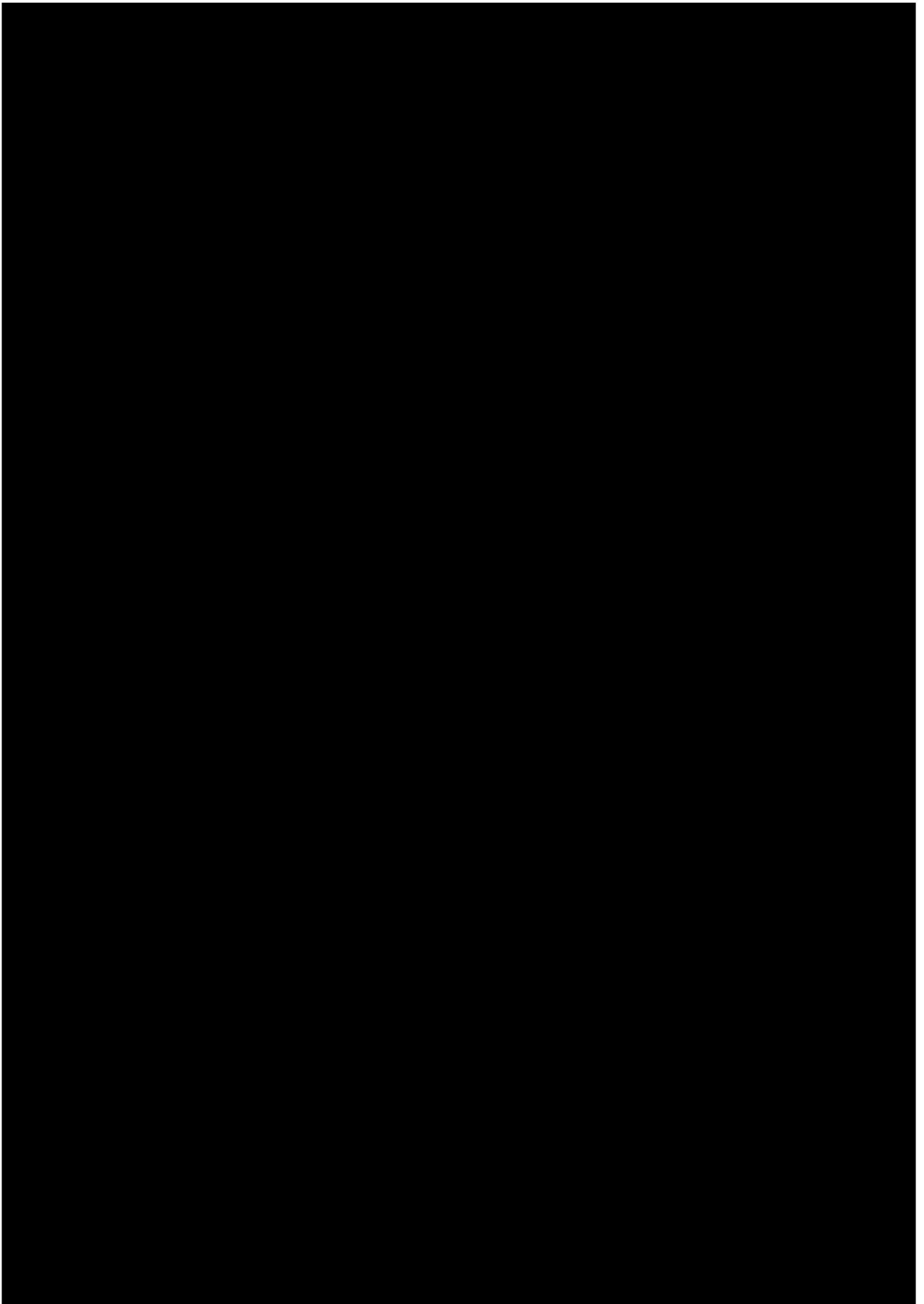
Appendix A

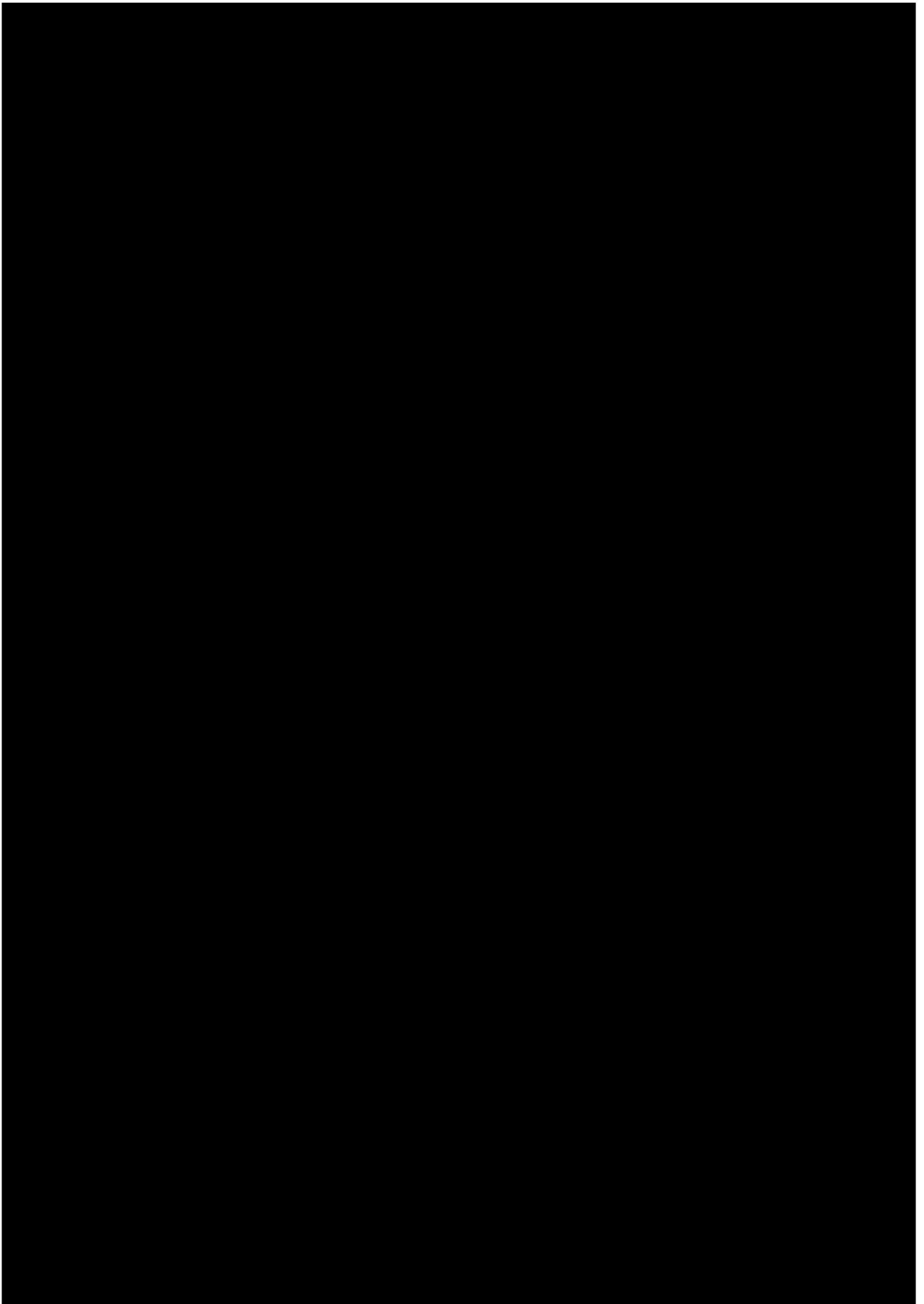


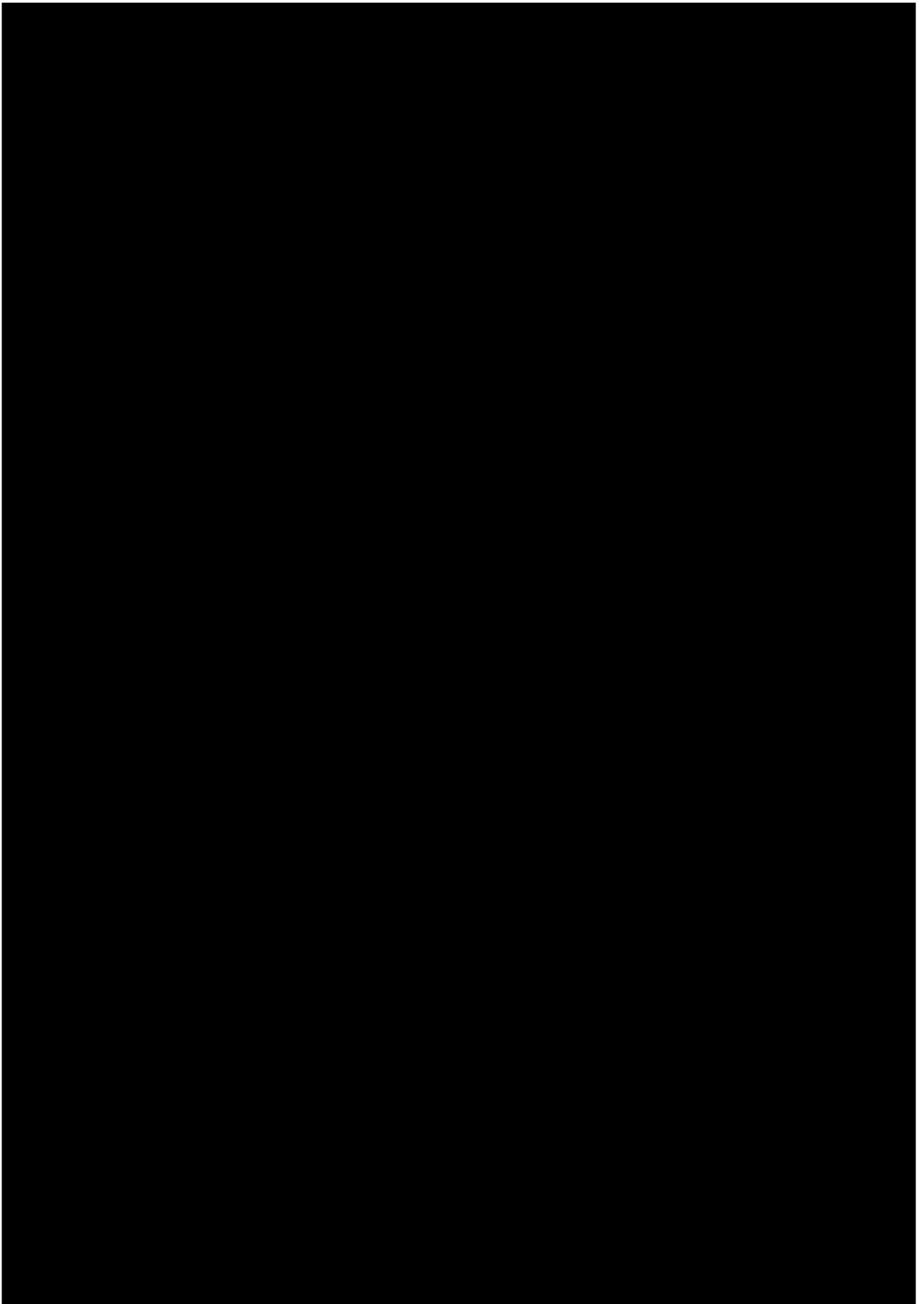


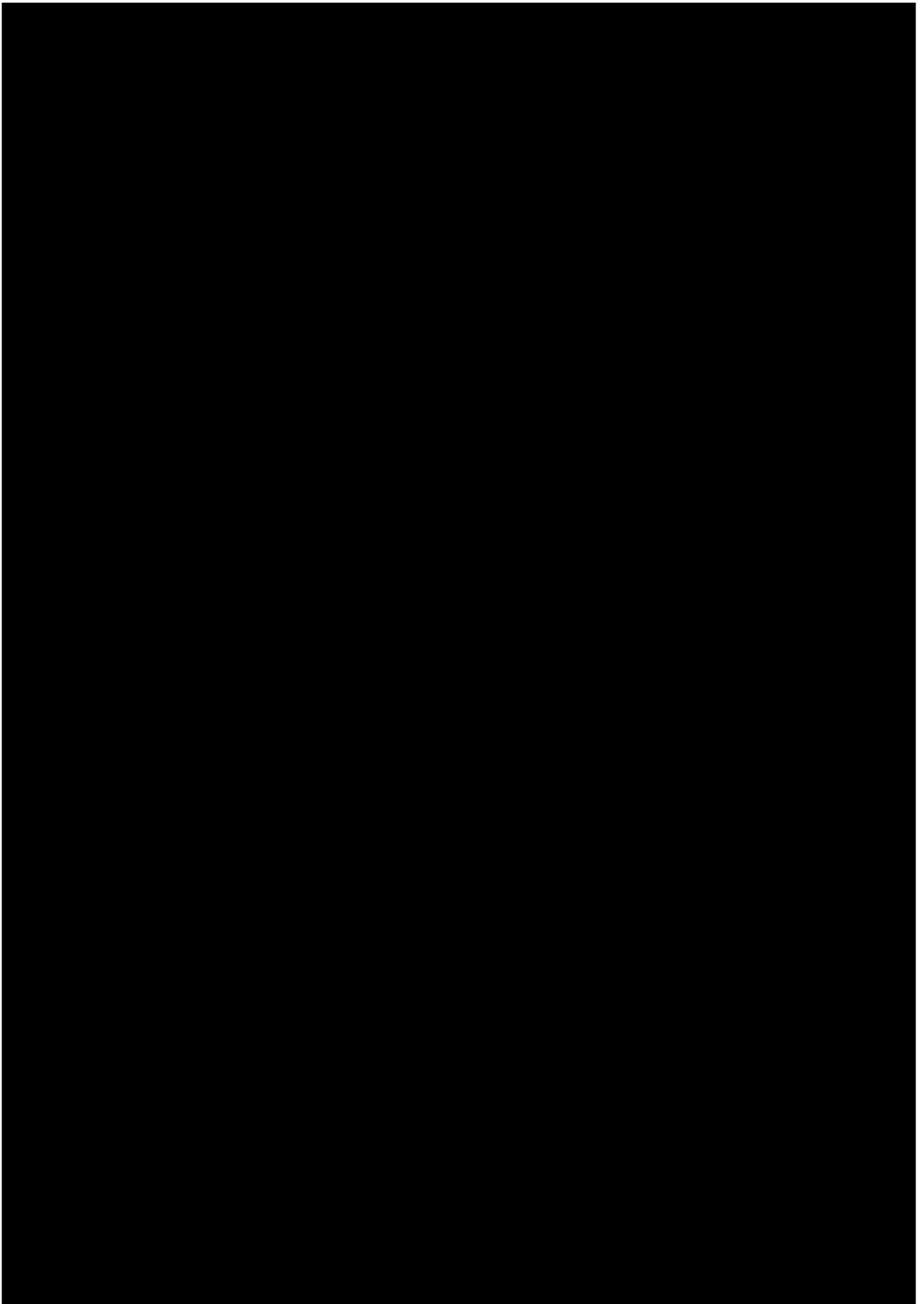


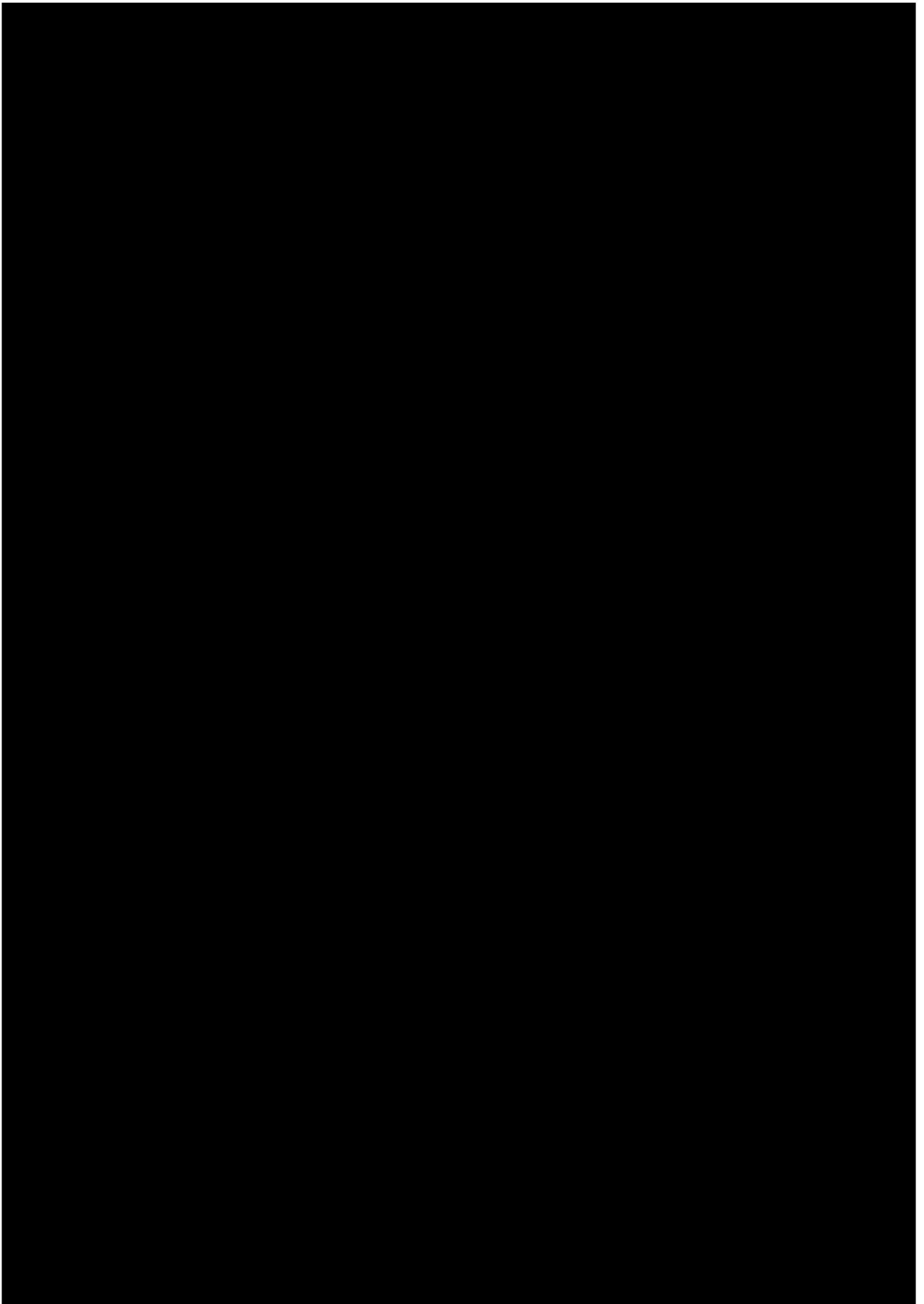


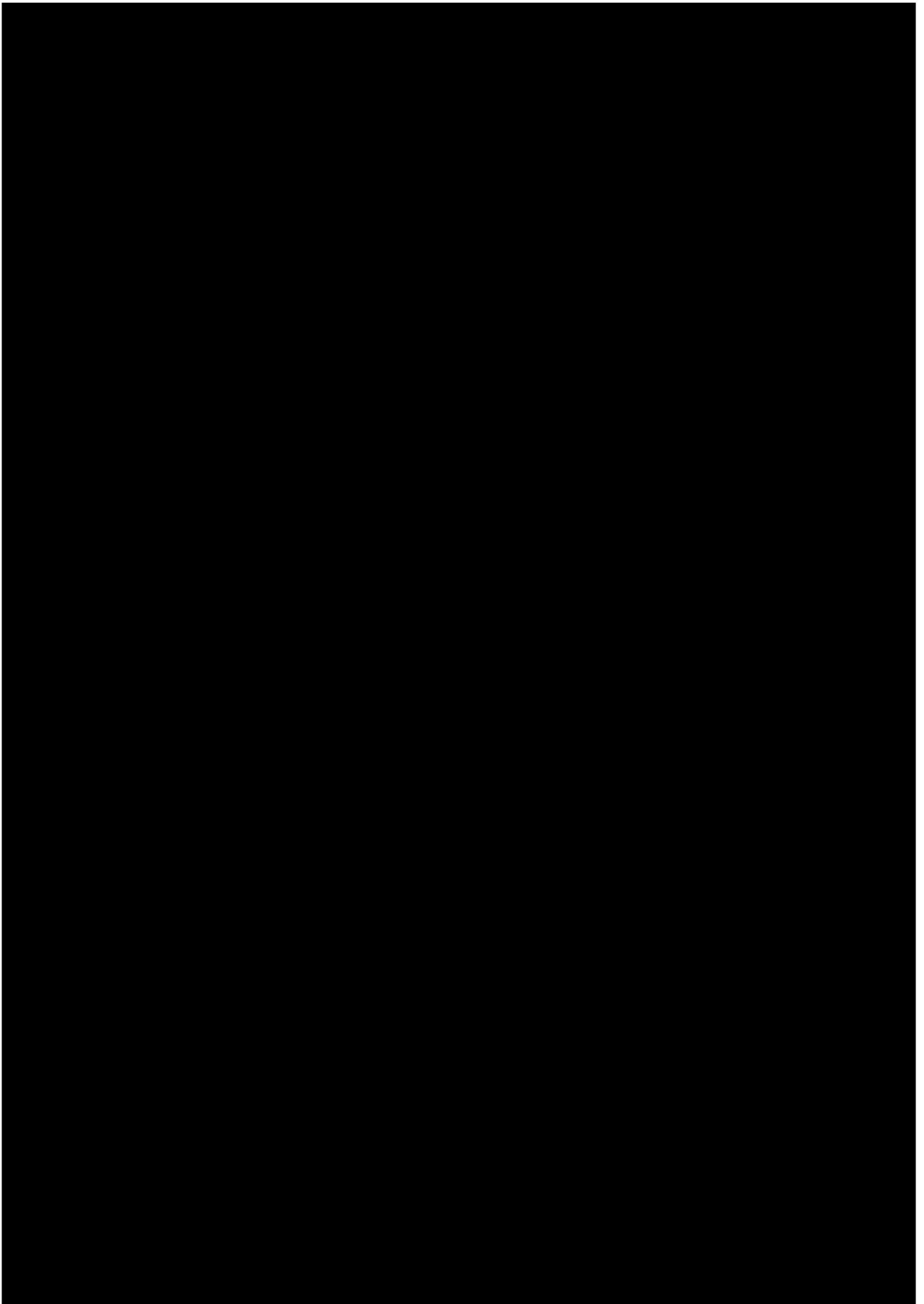




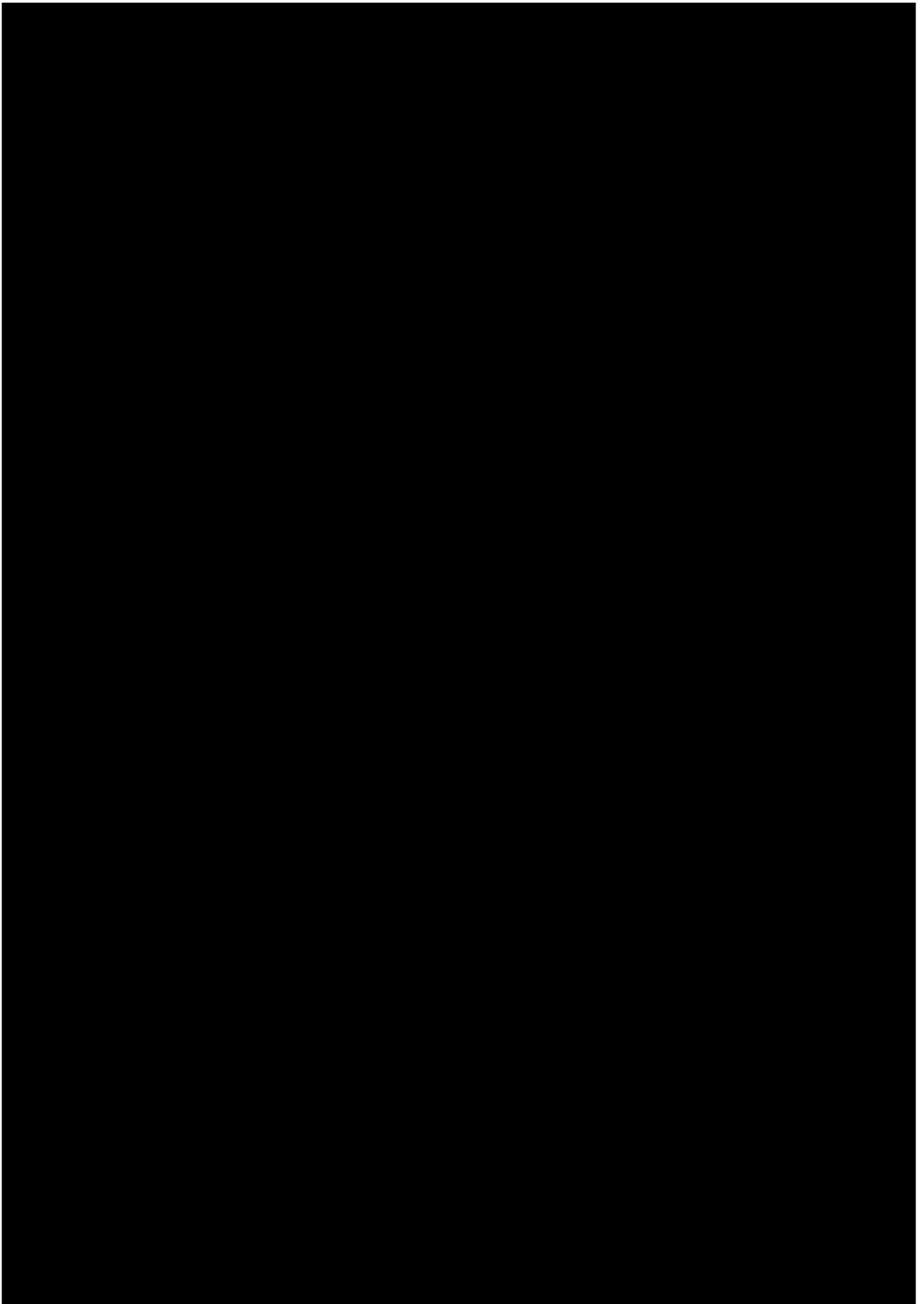


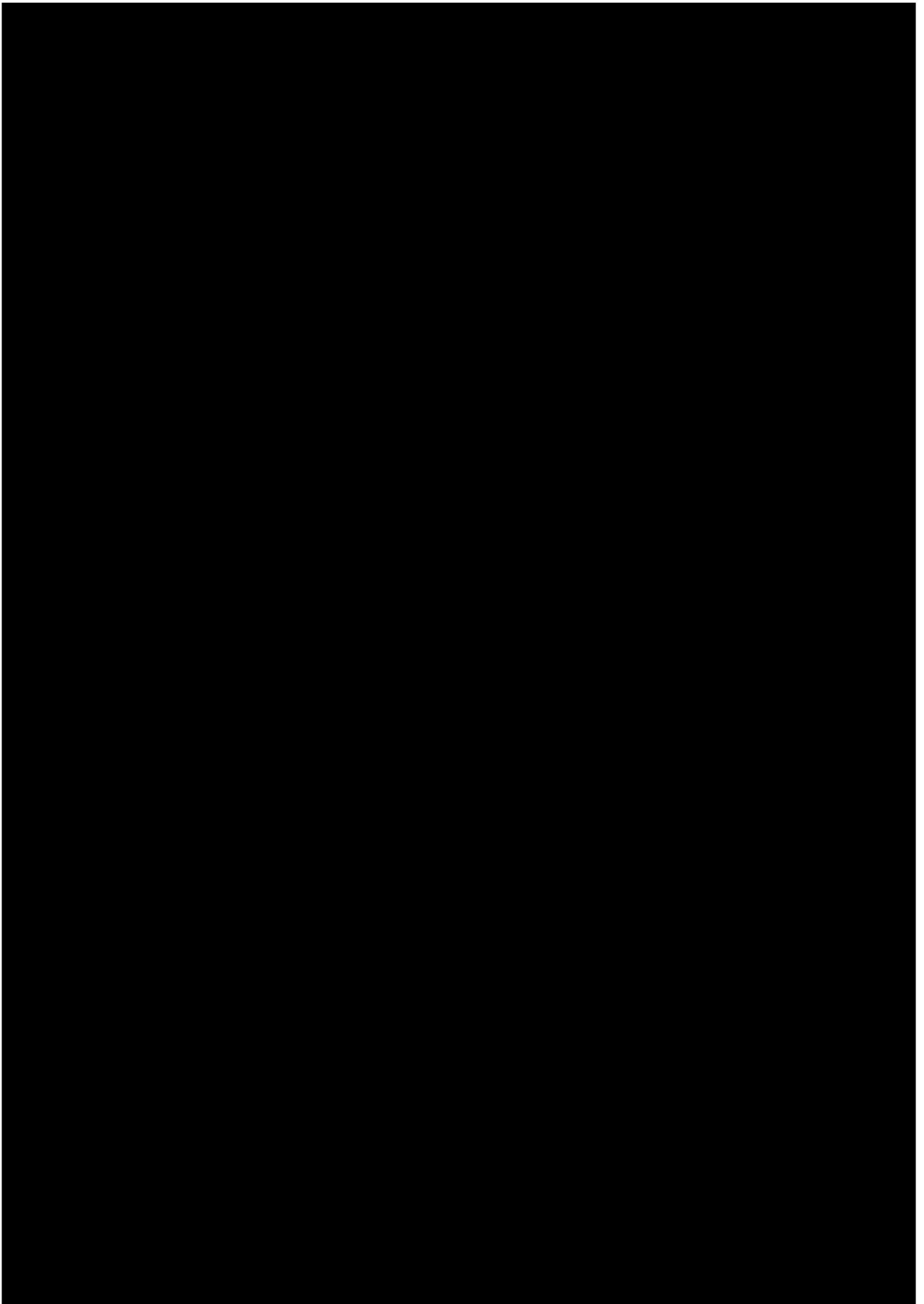


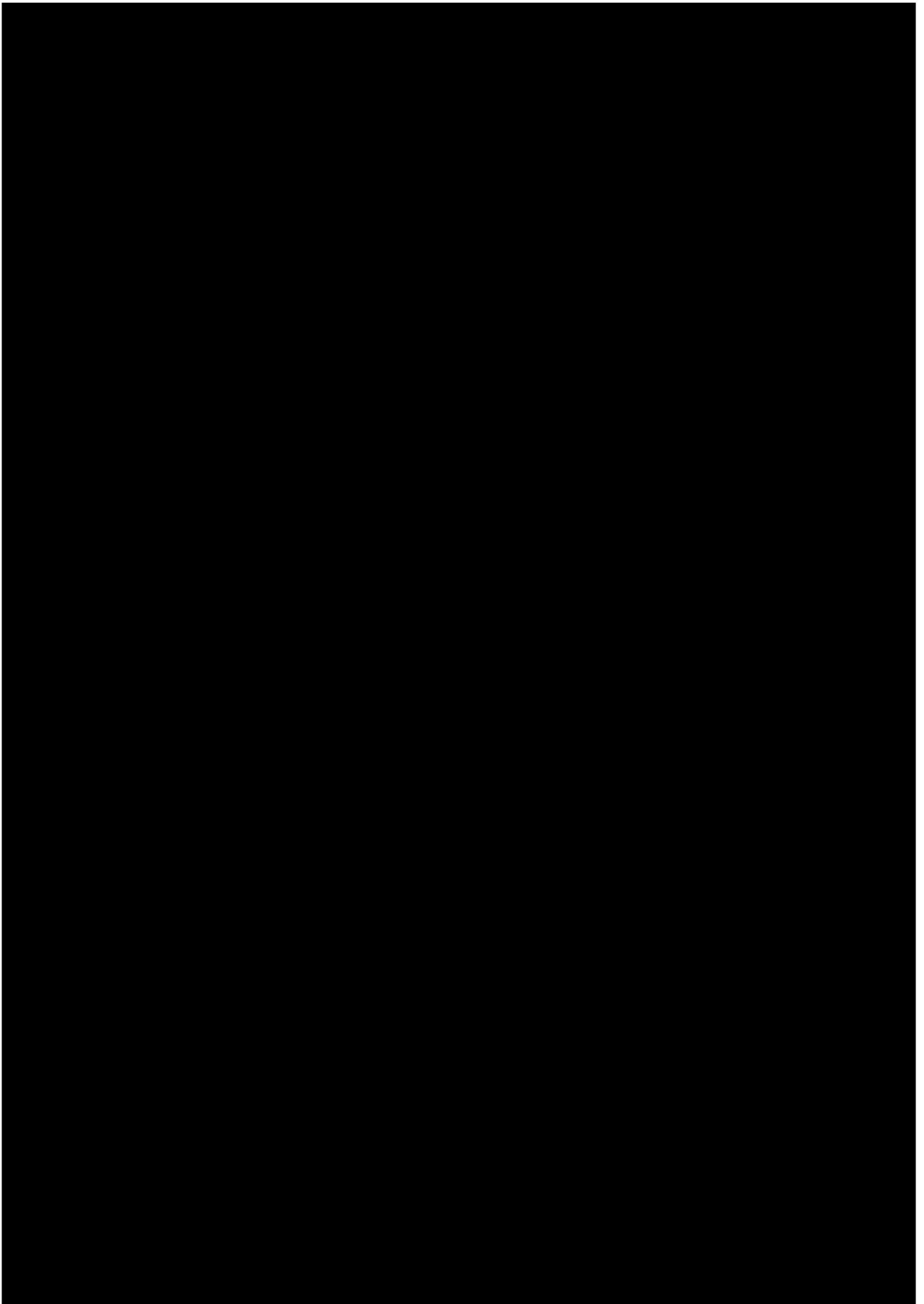


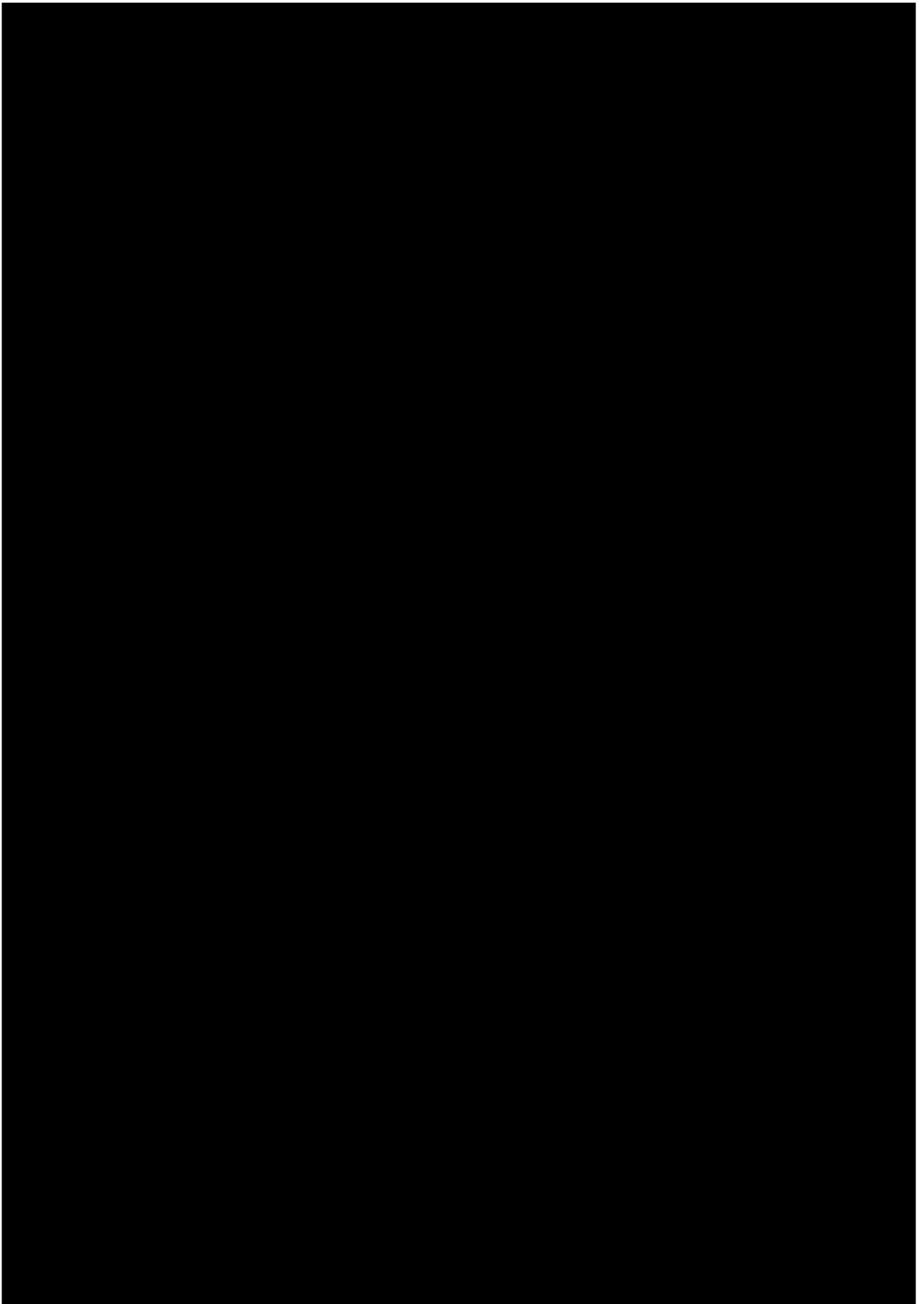


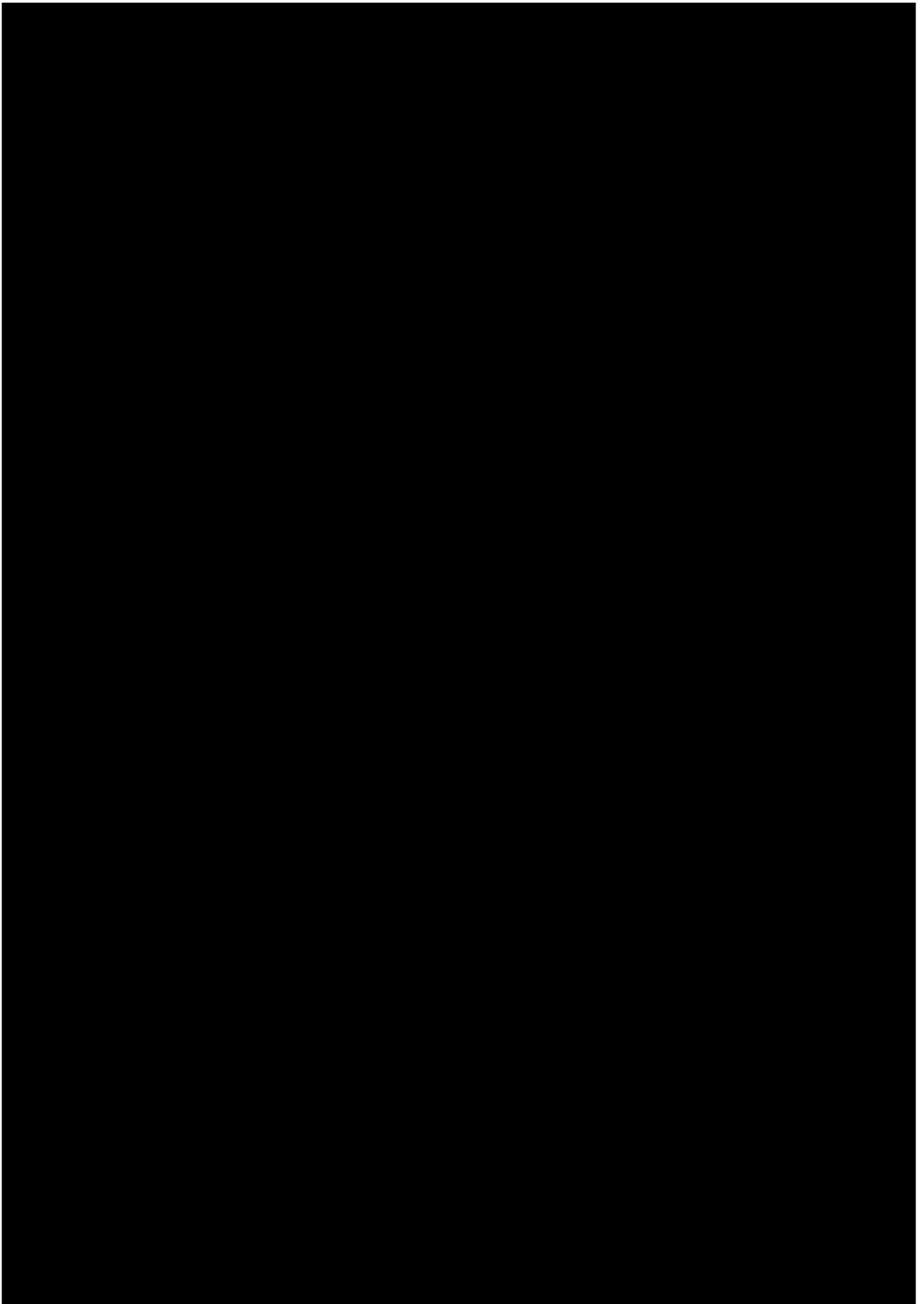
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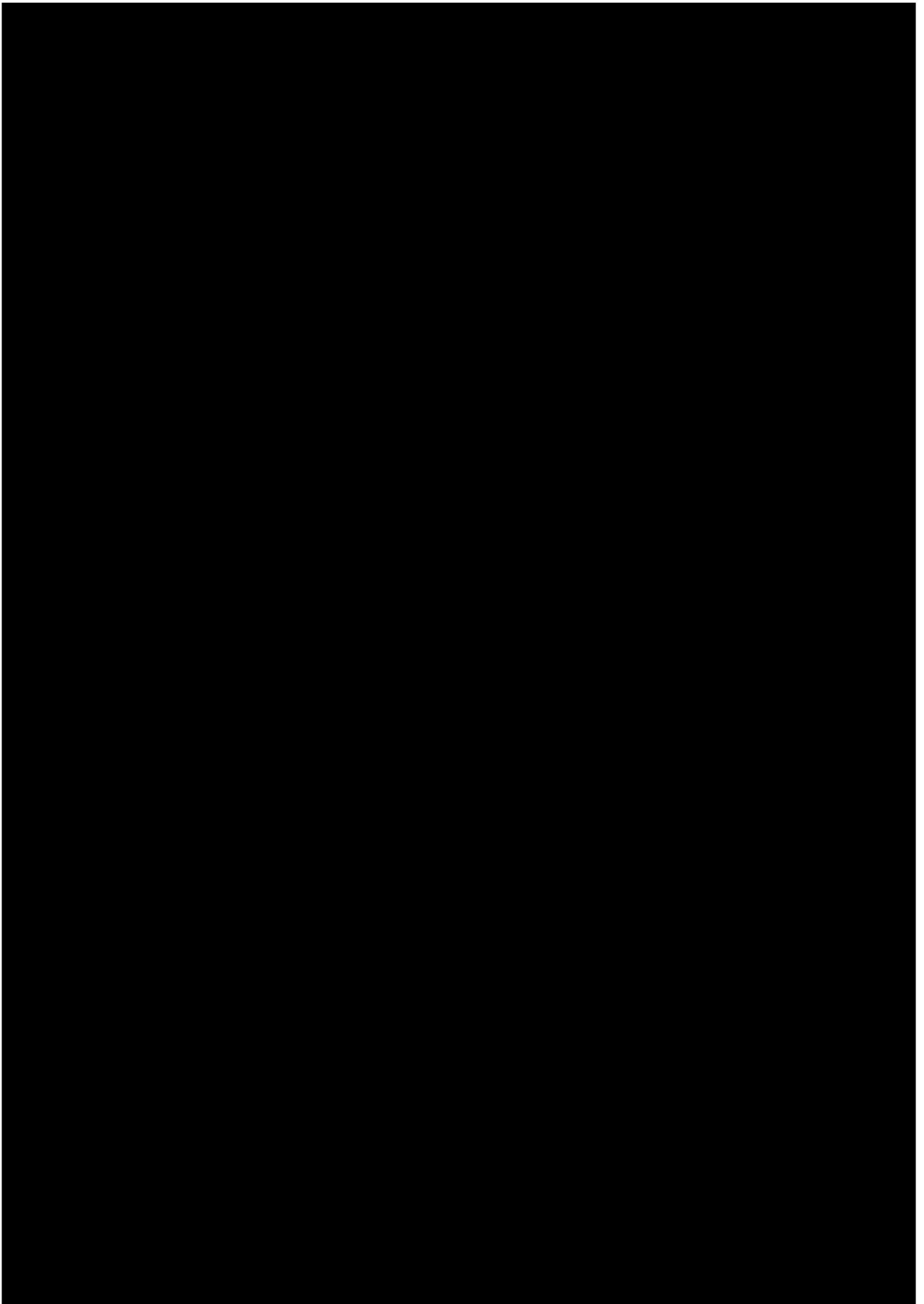


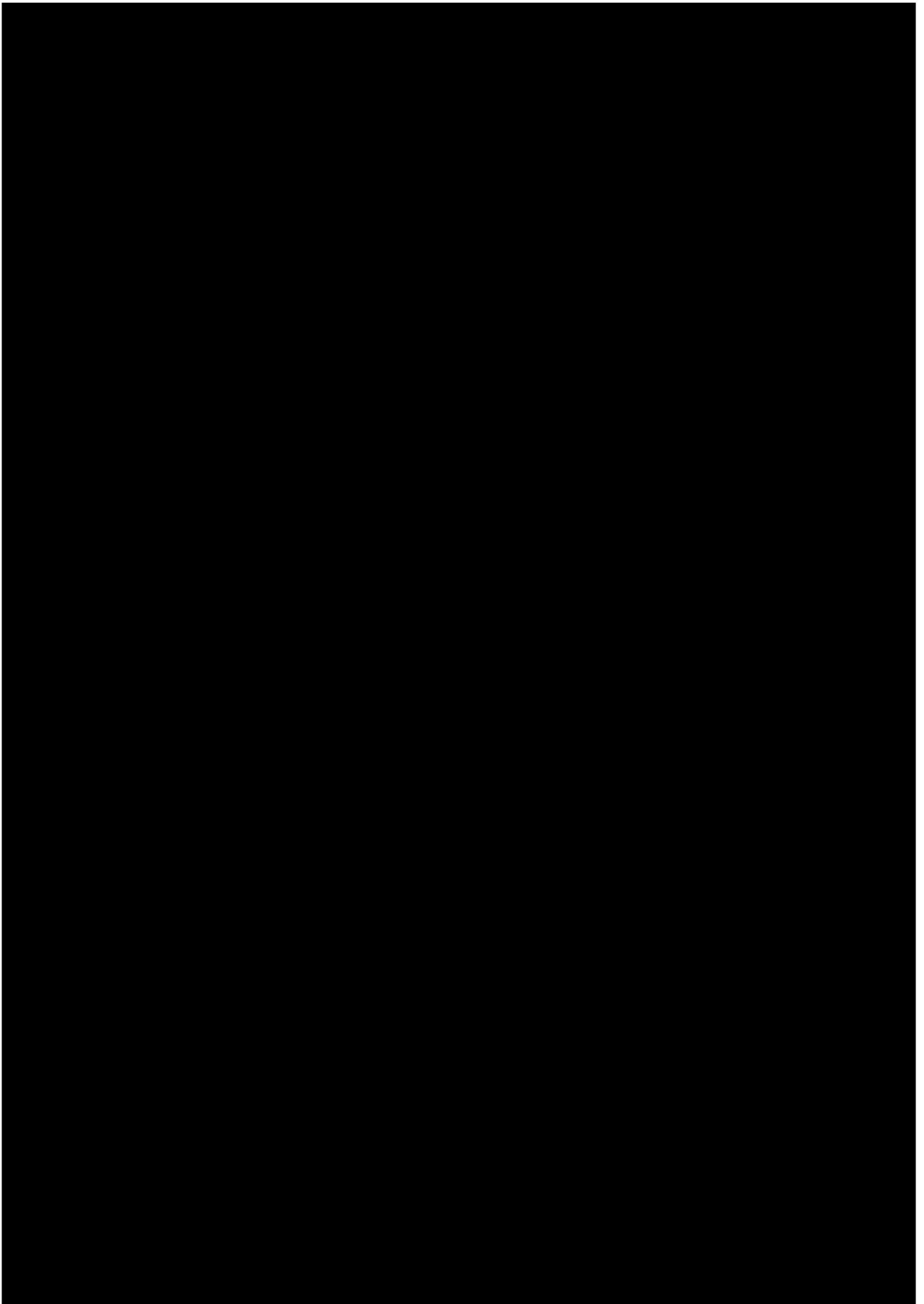


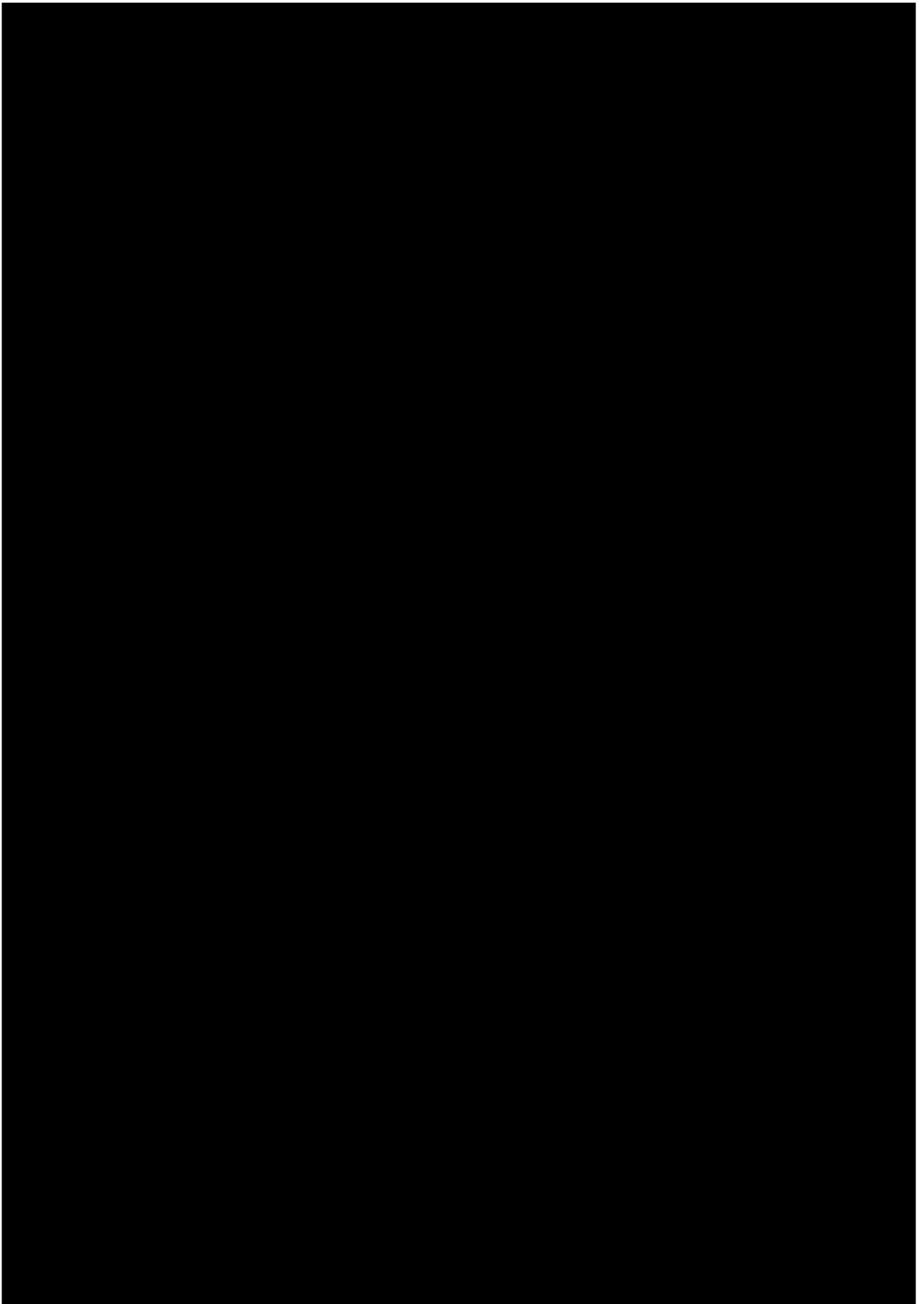


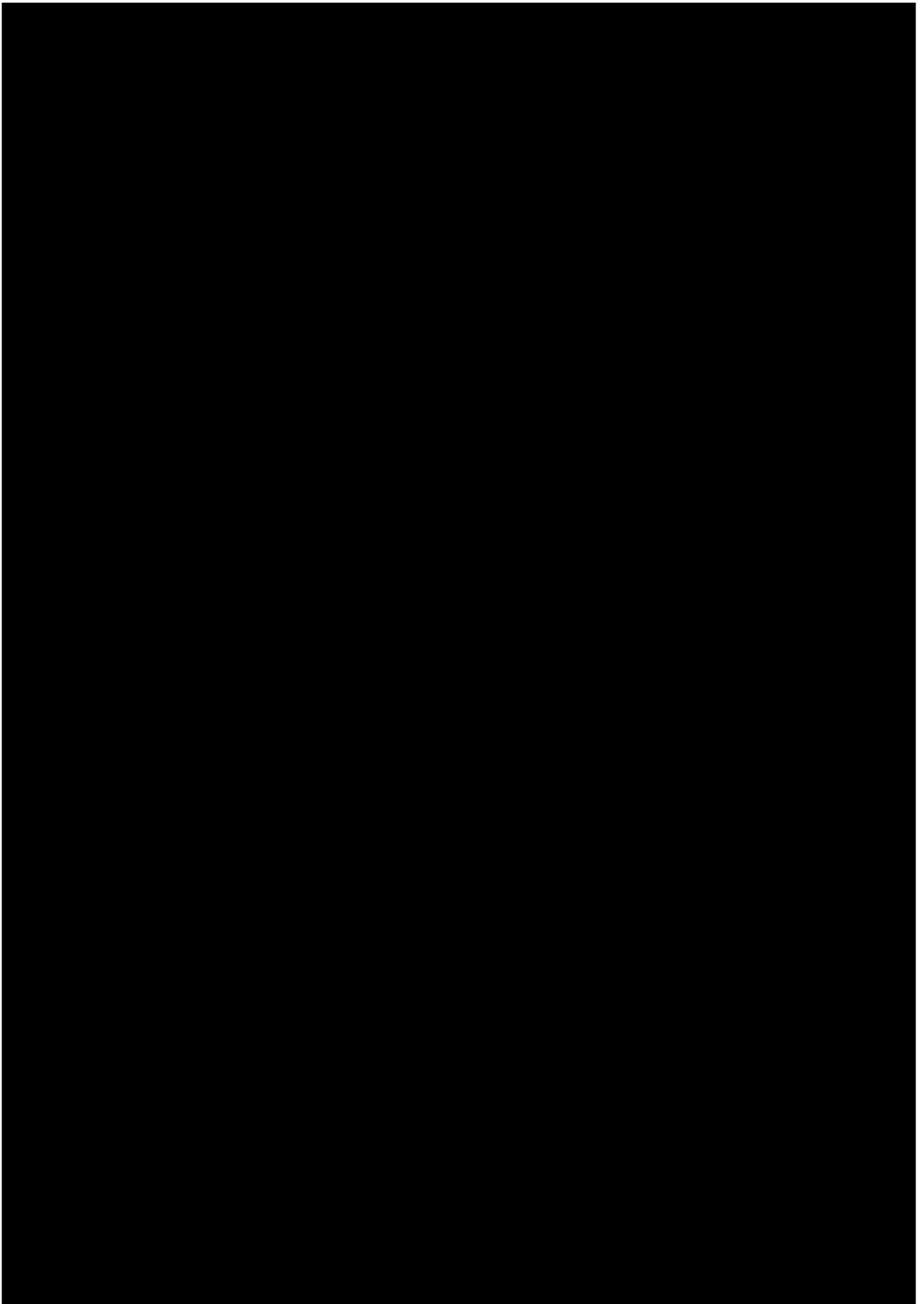


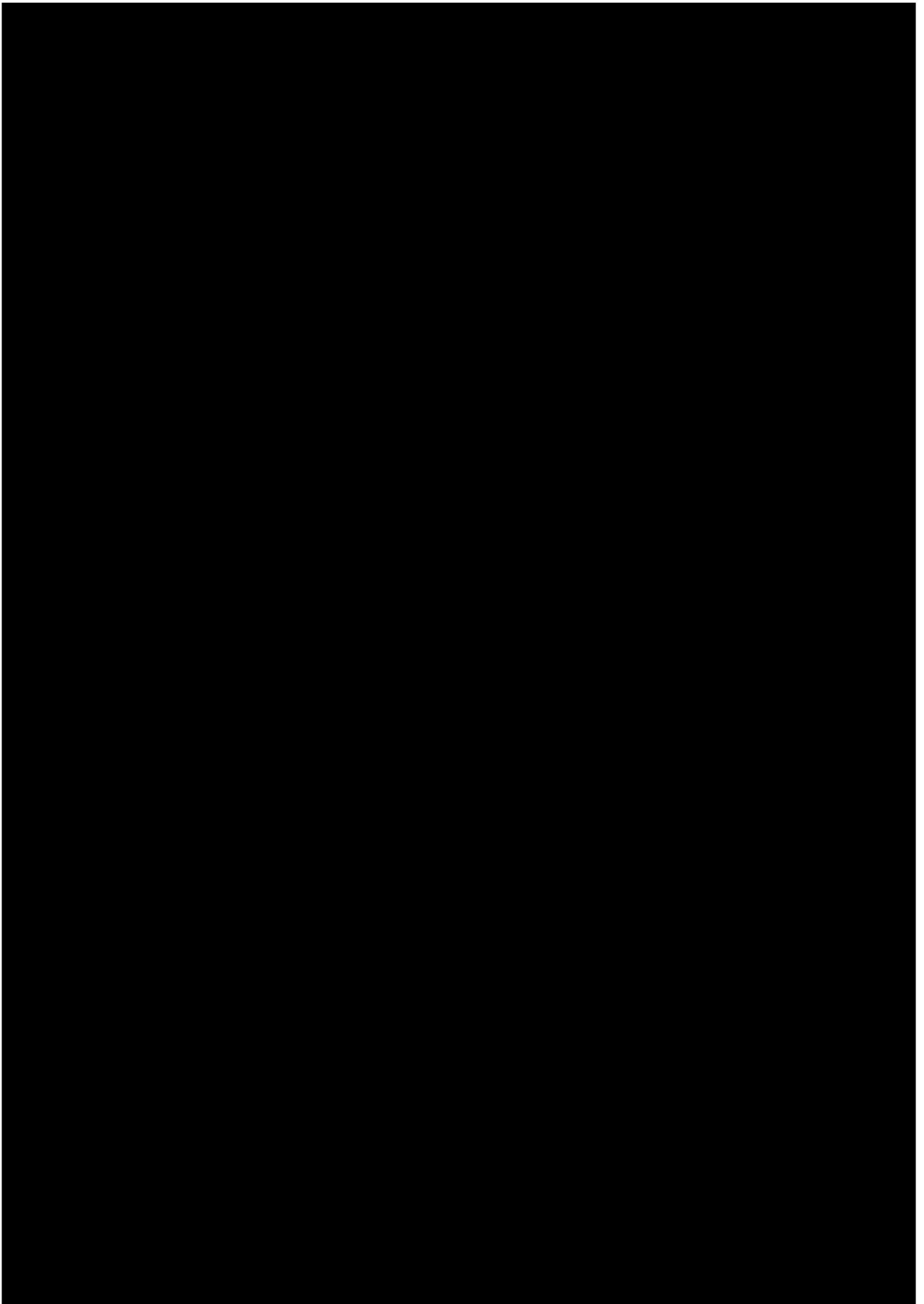


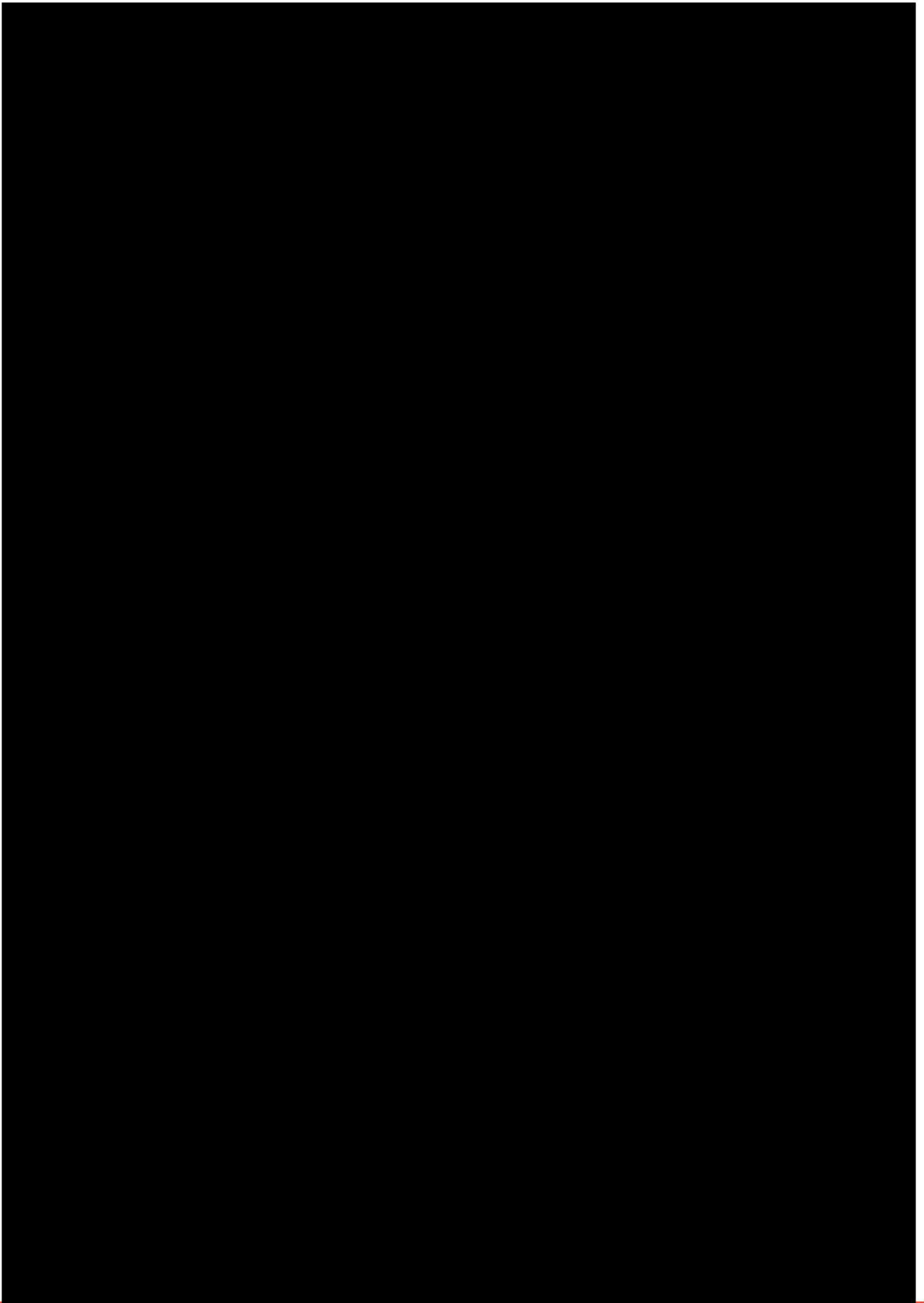


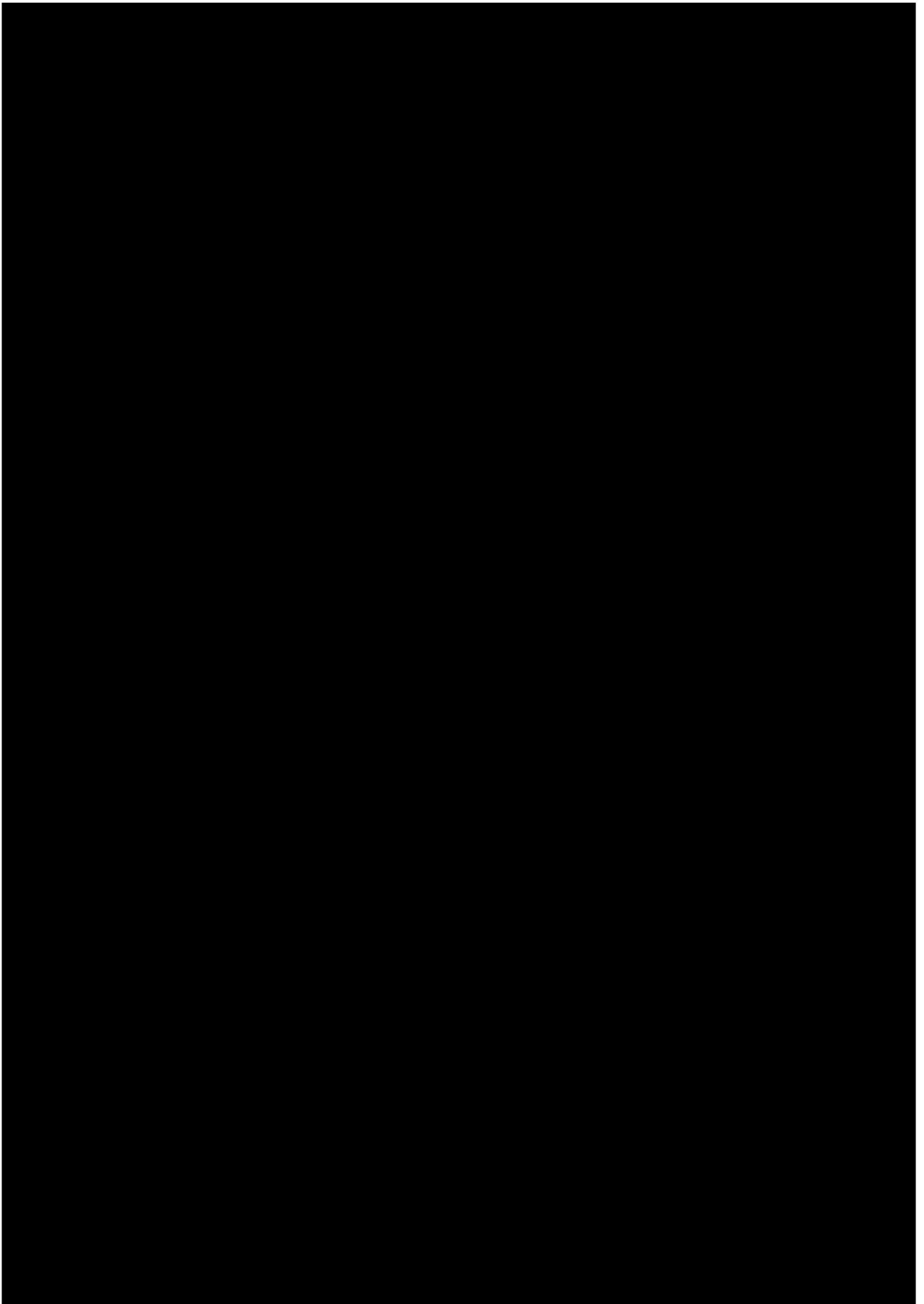


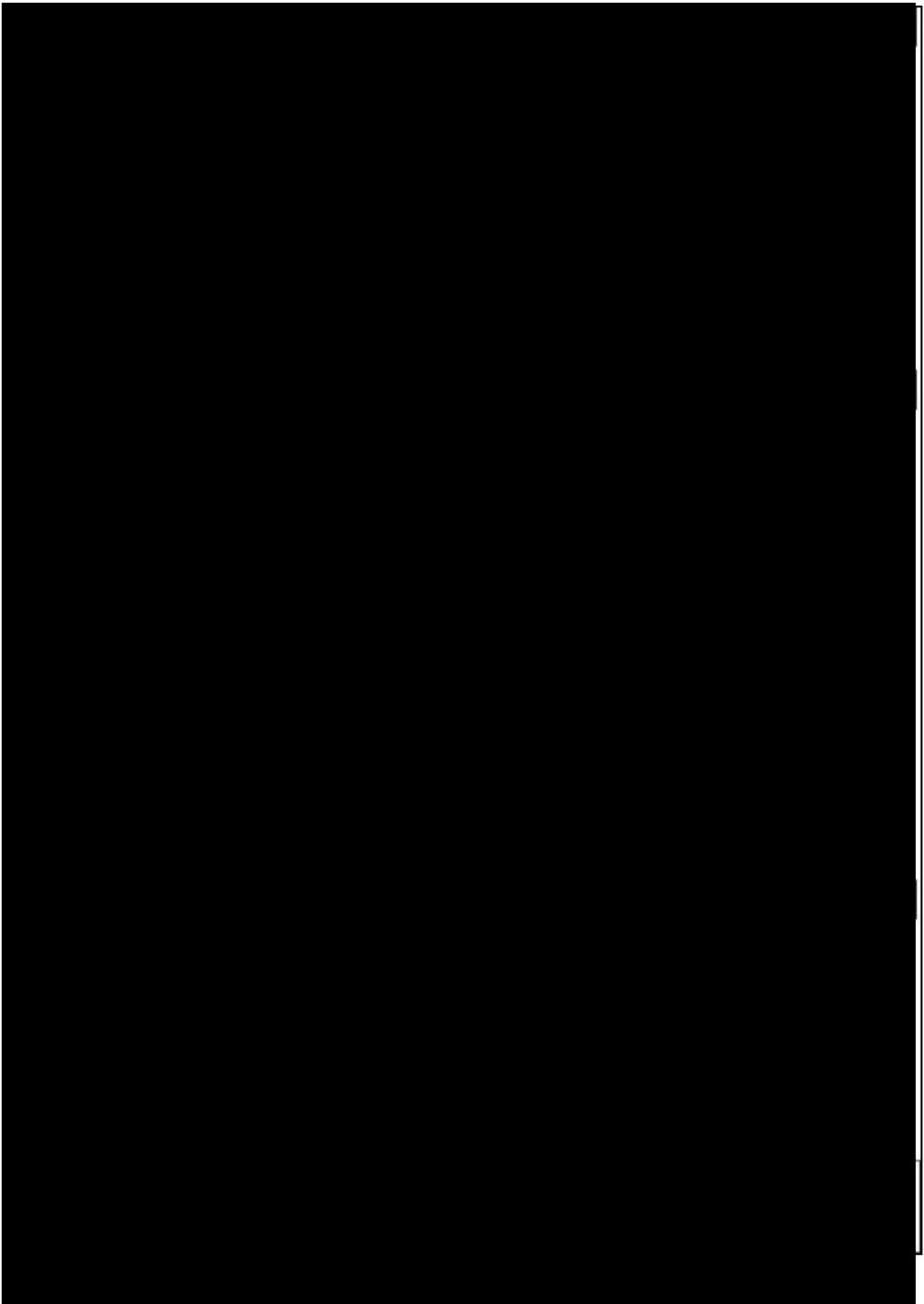


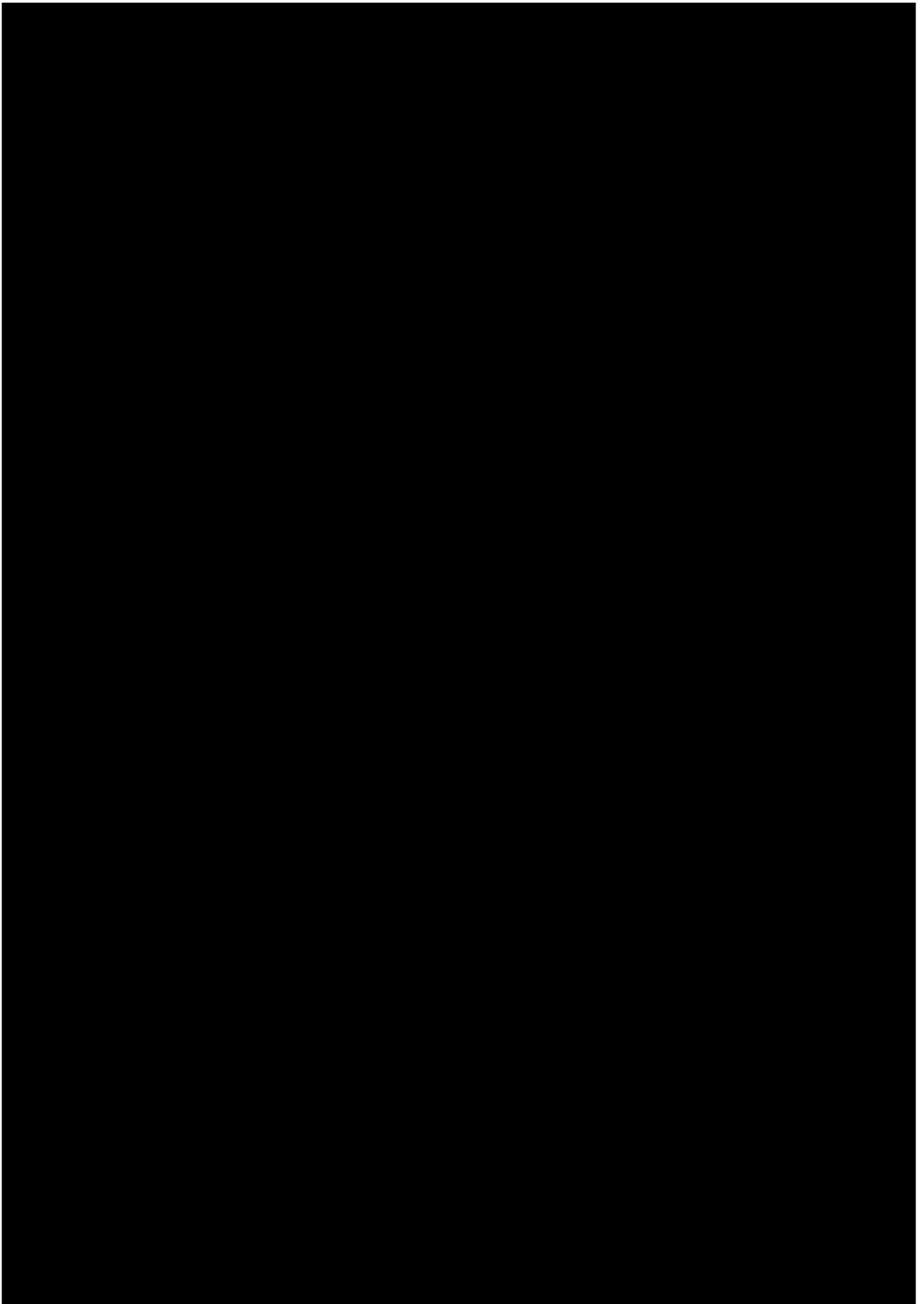


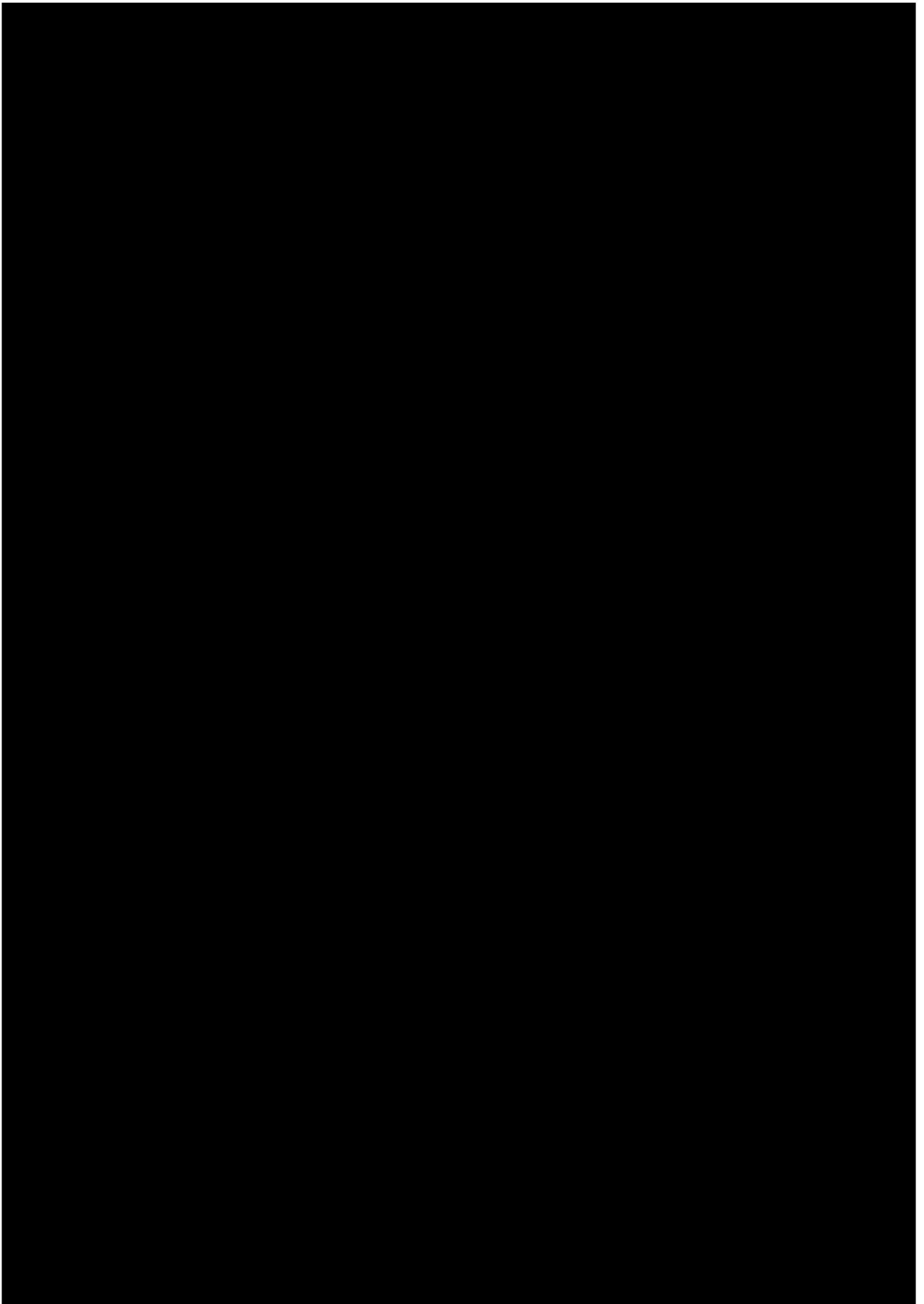


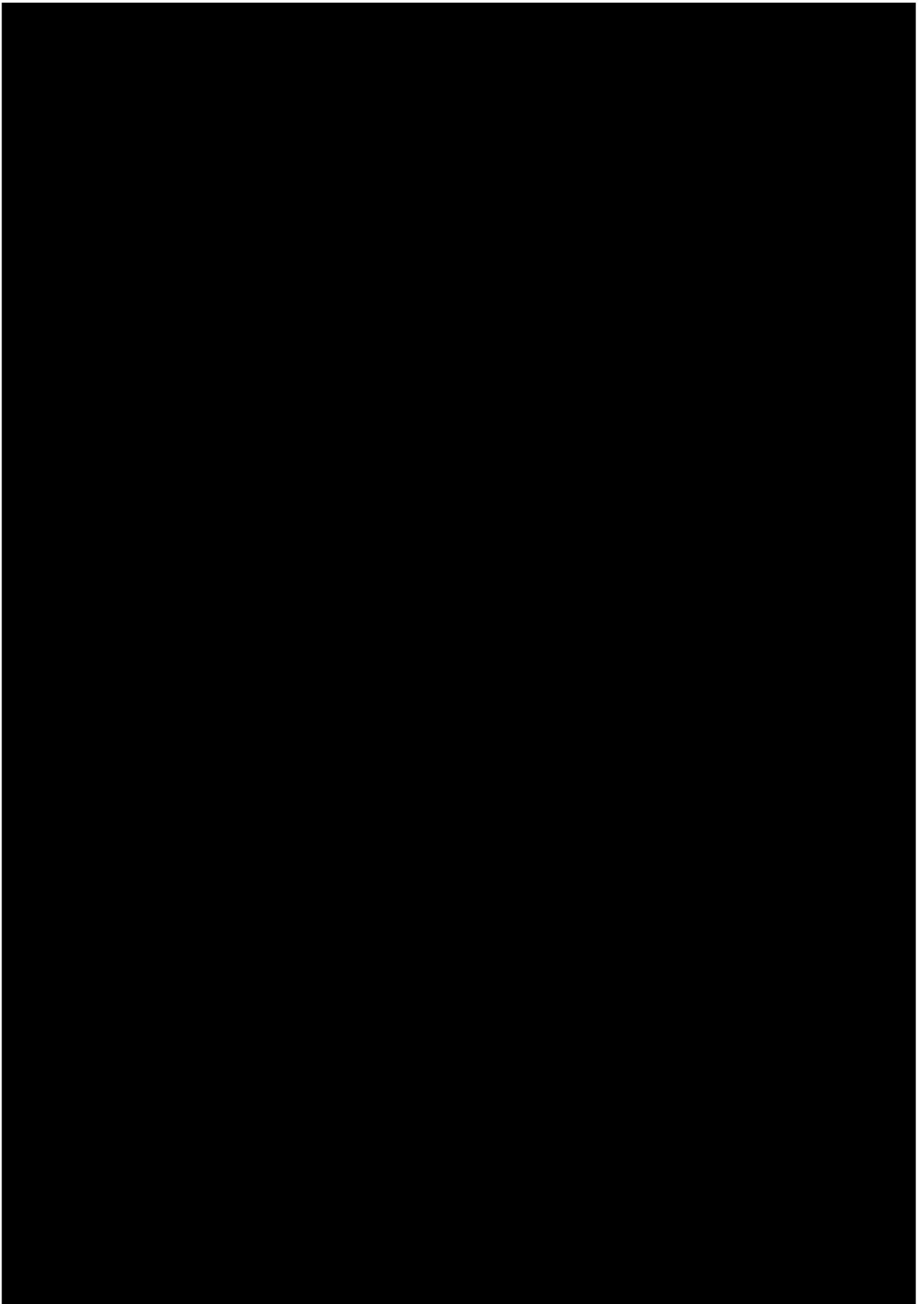


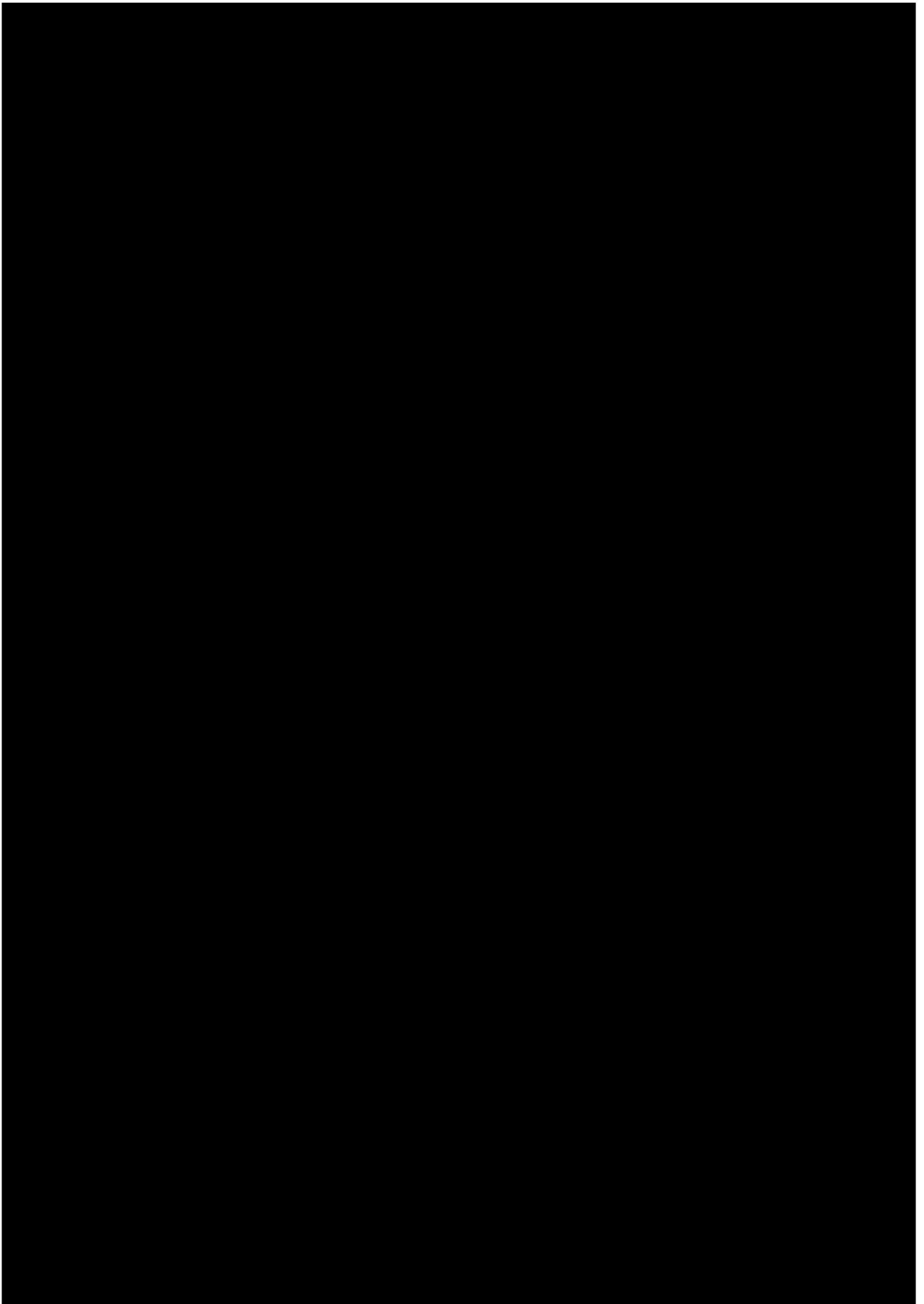


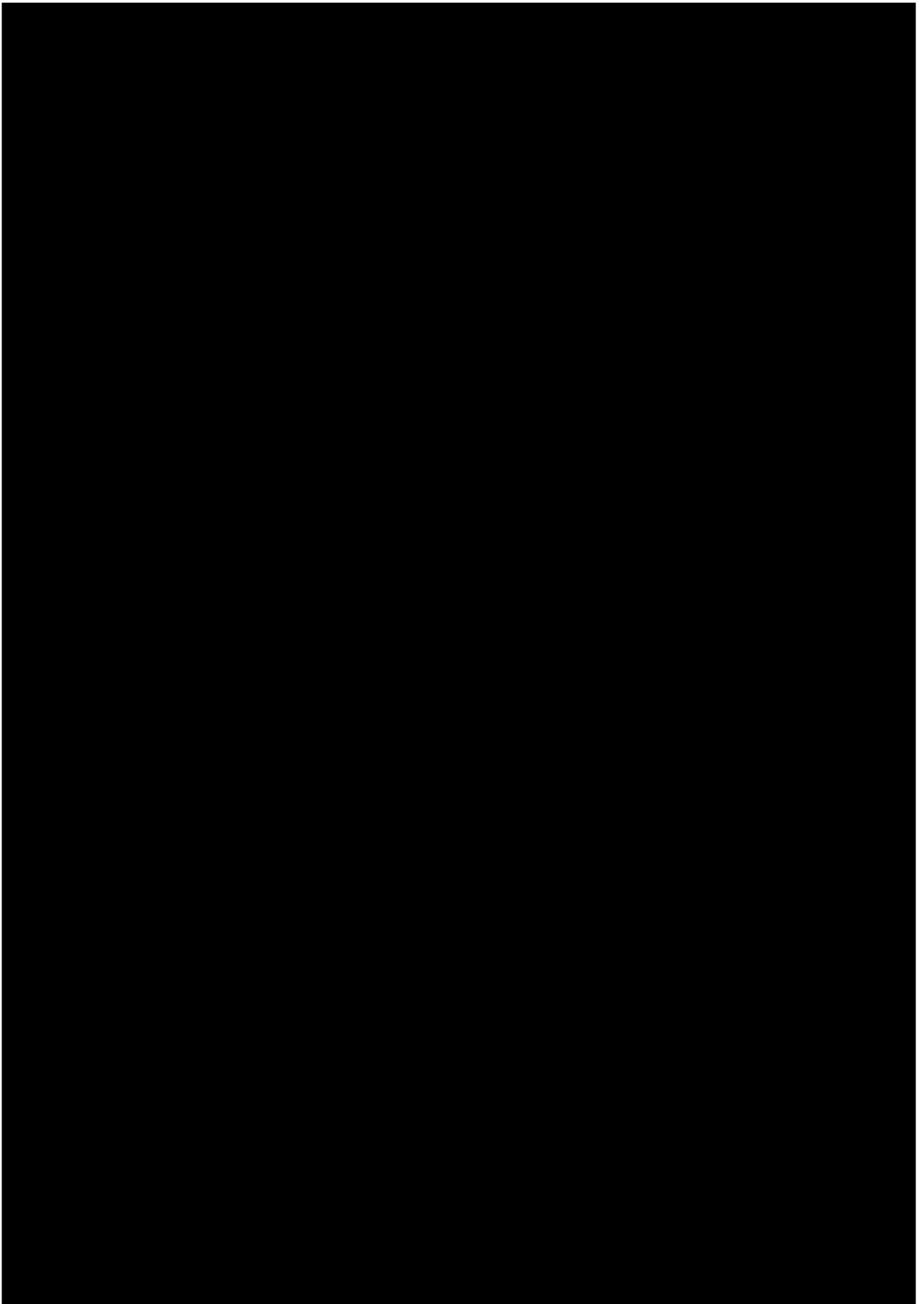


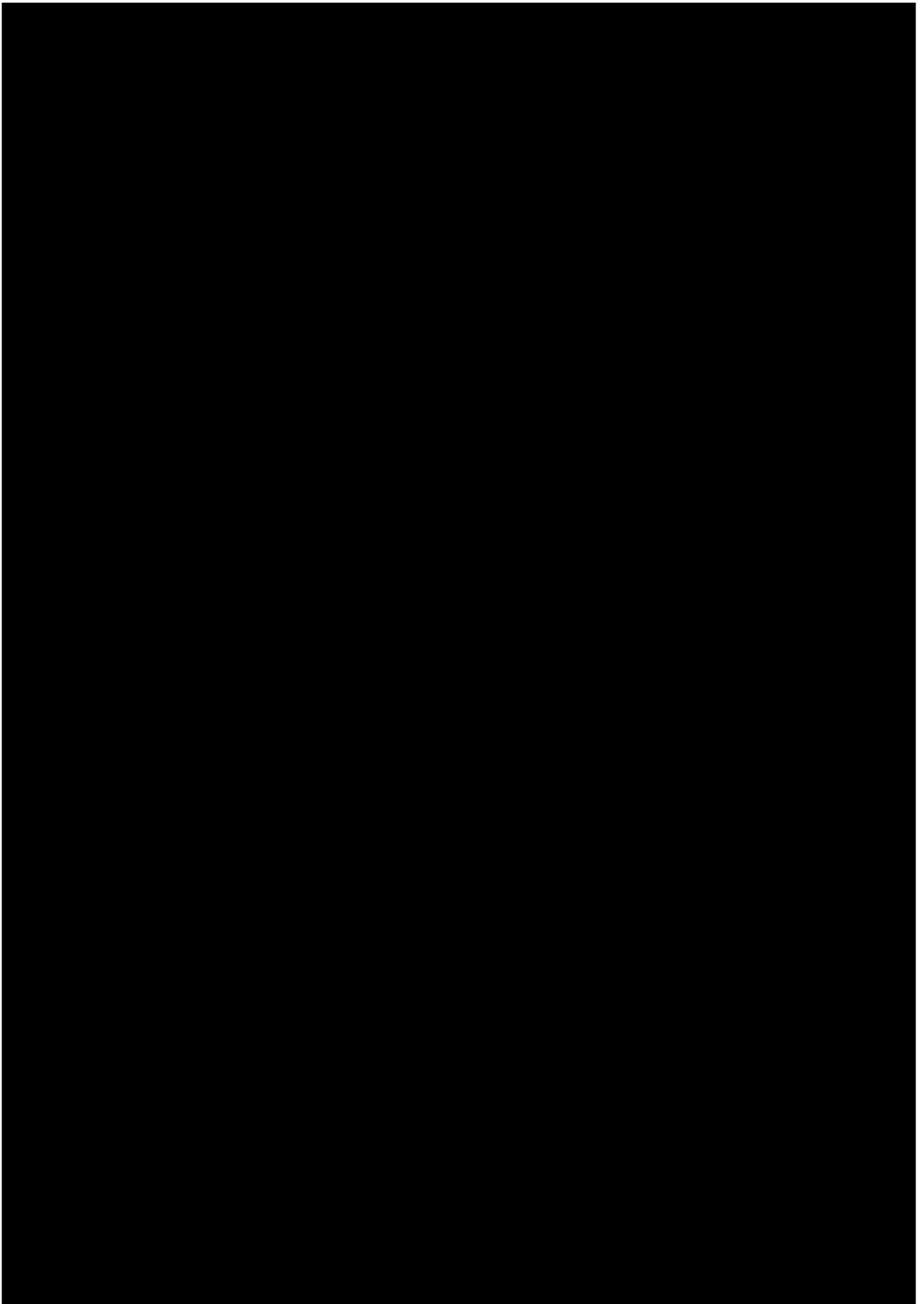


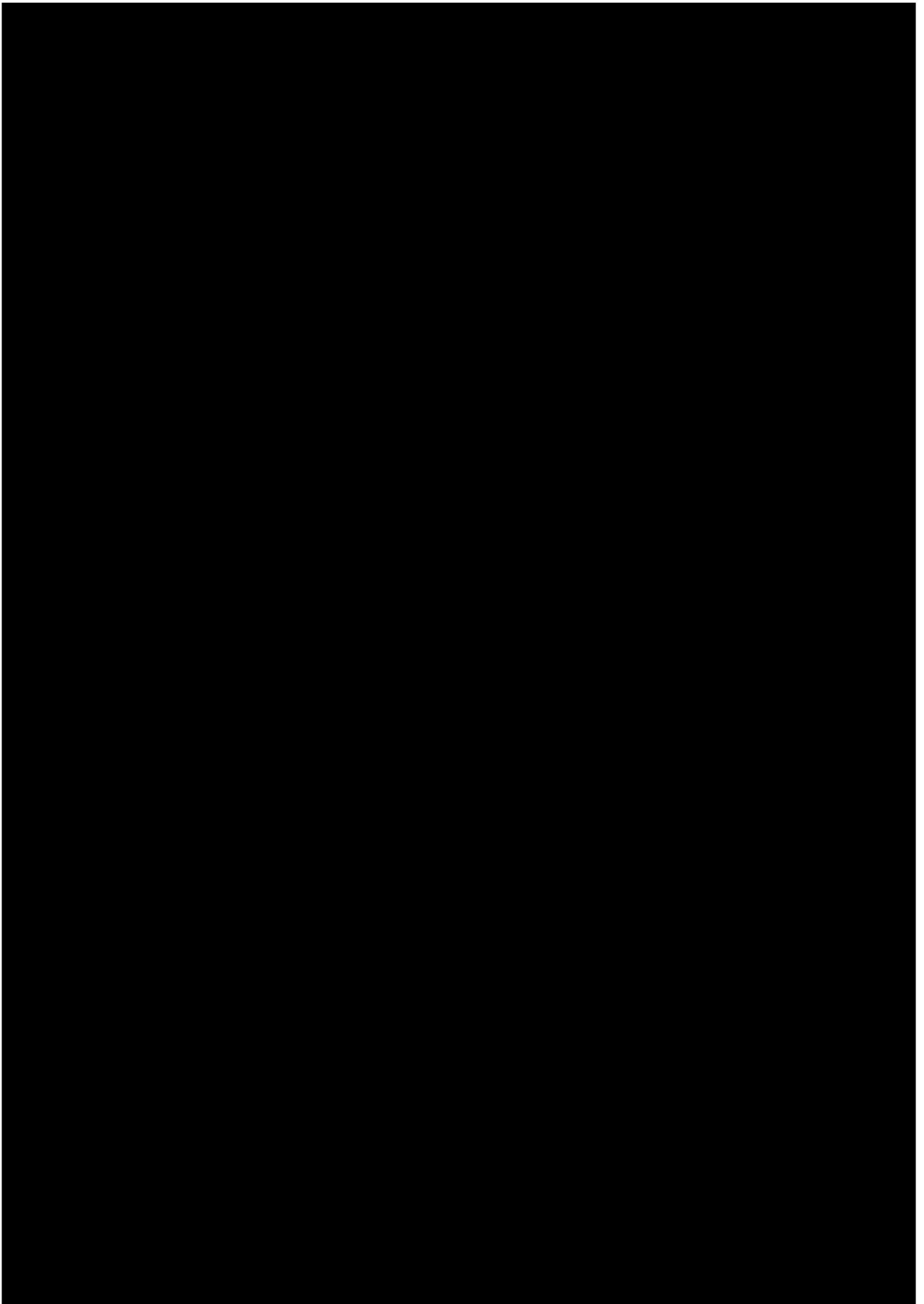


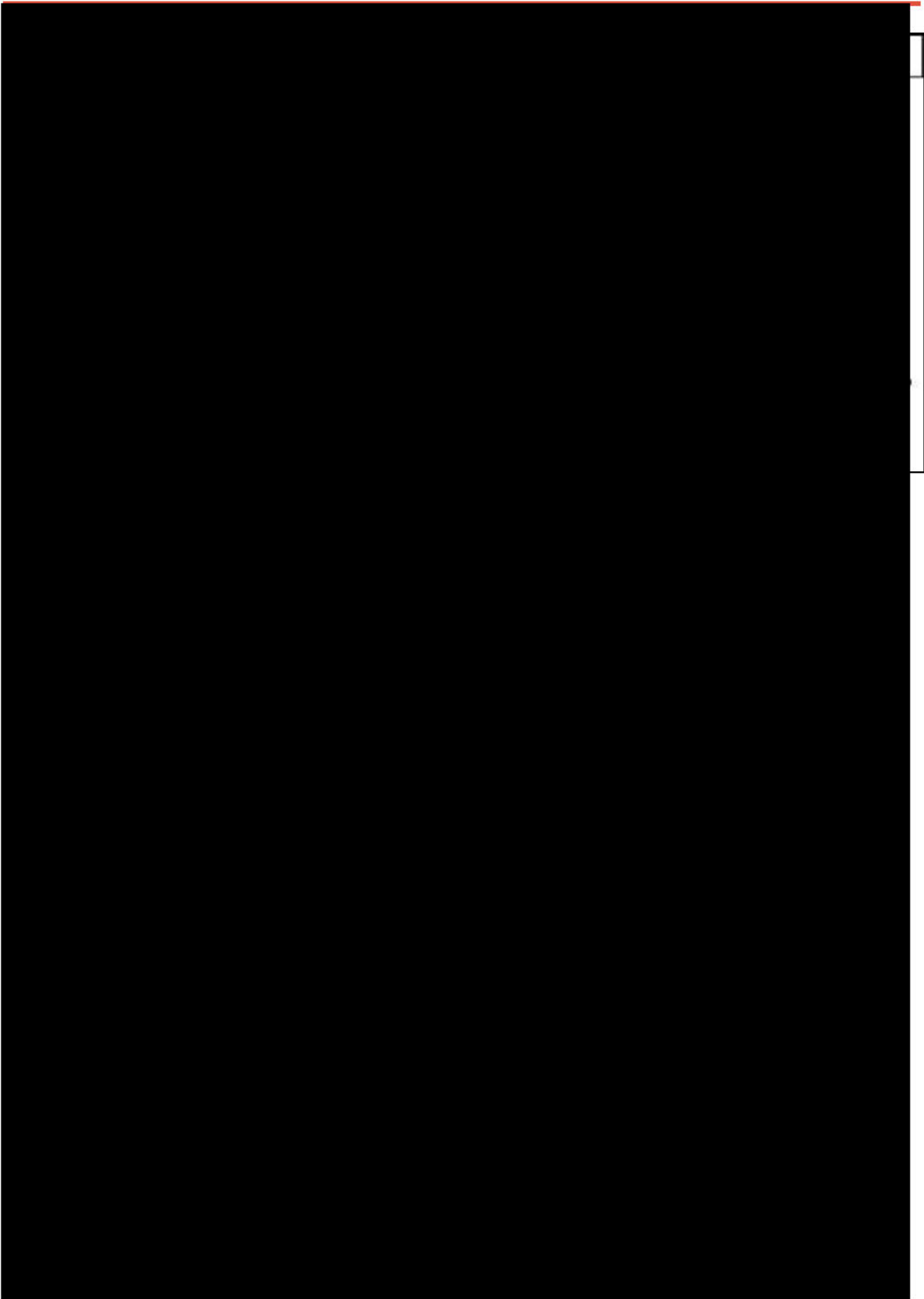




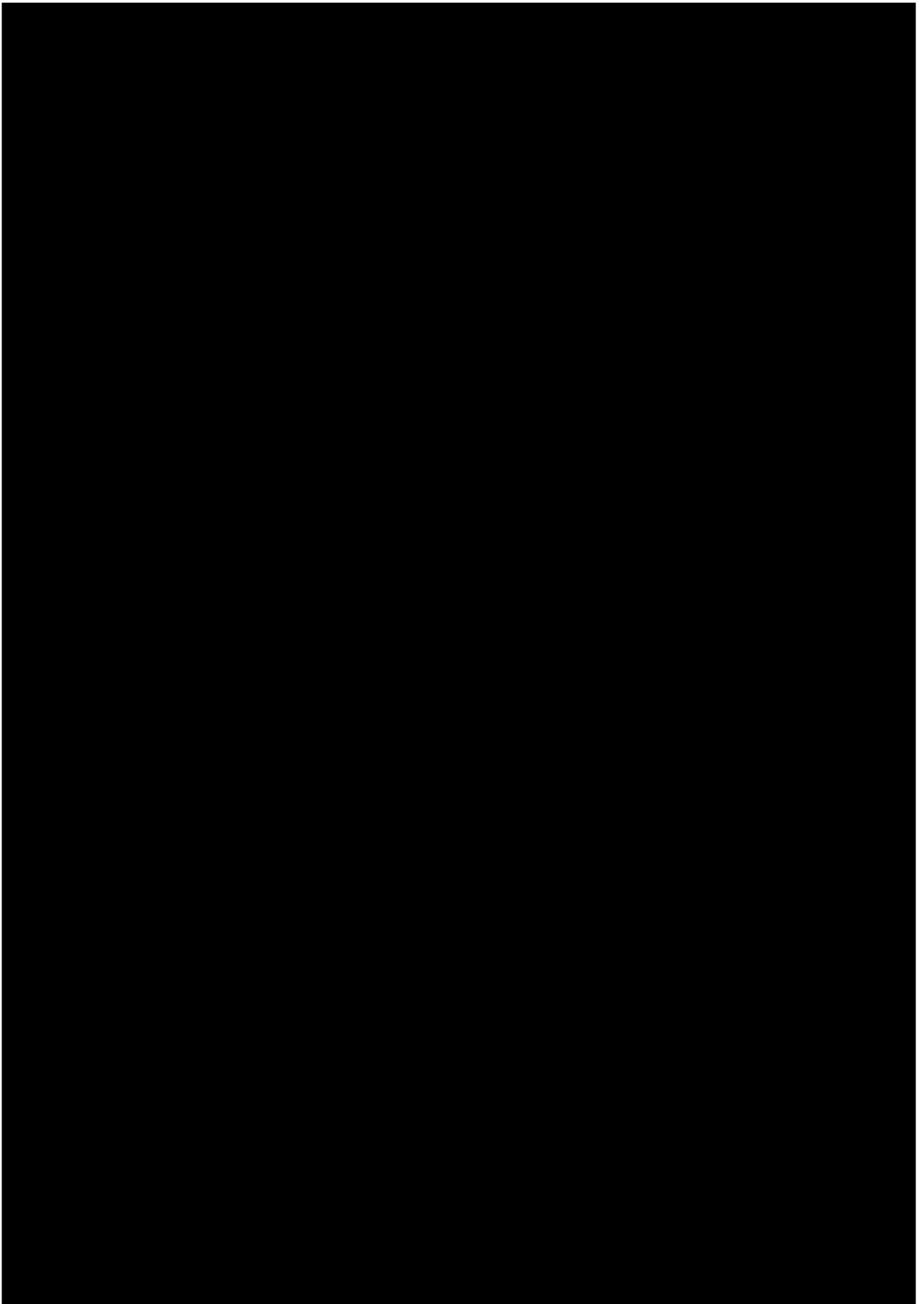


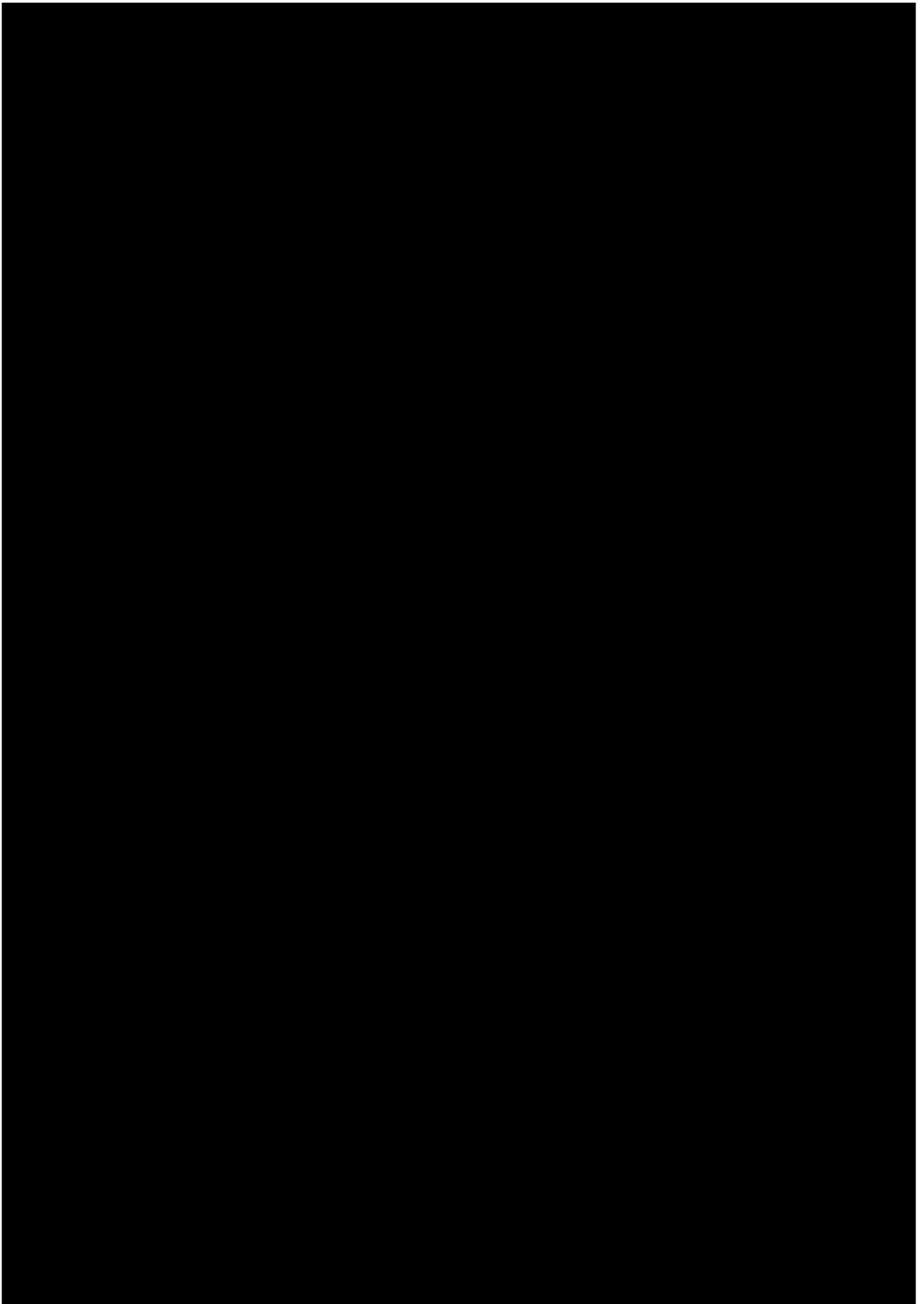


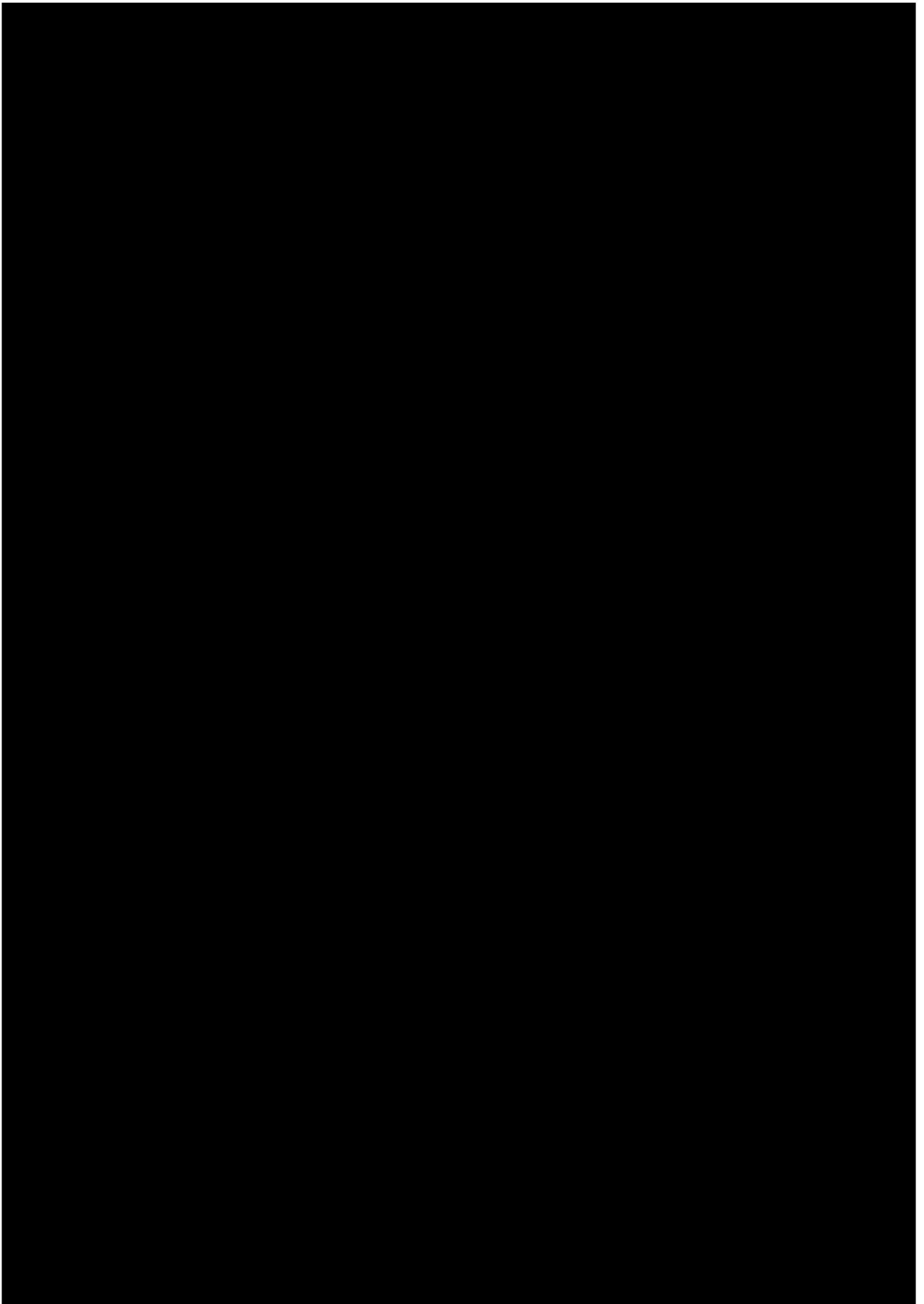


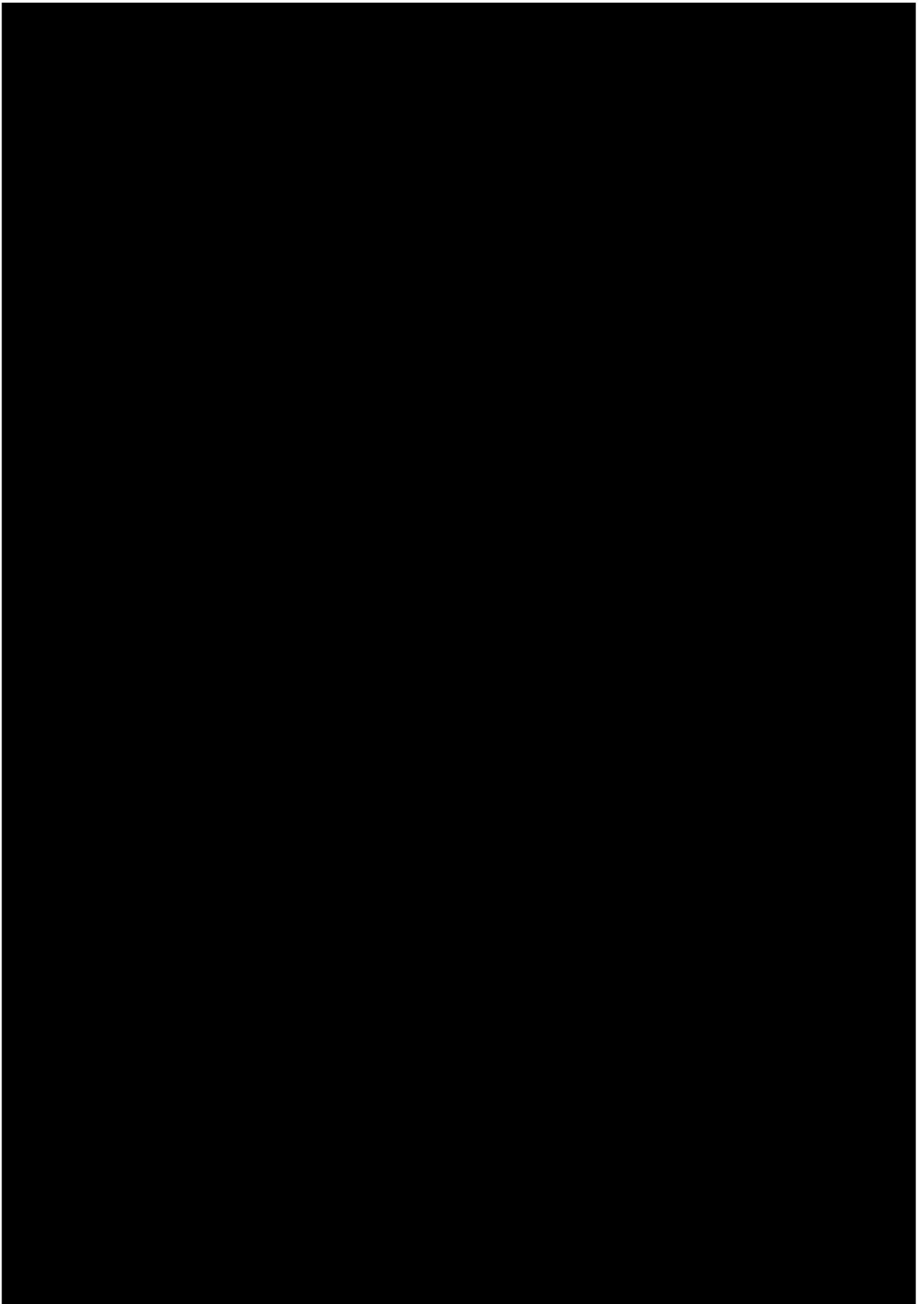


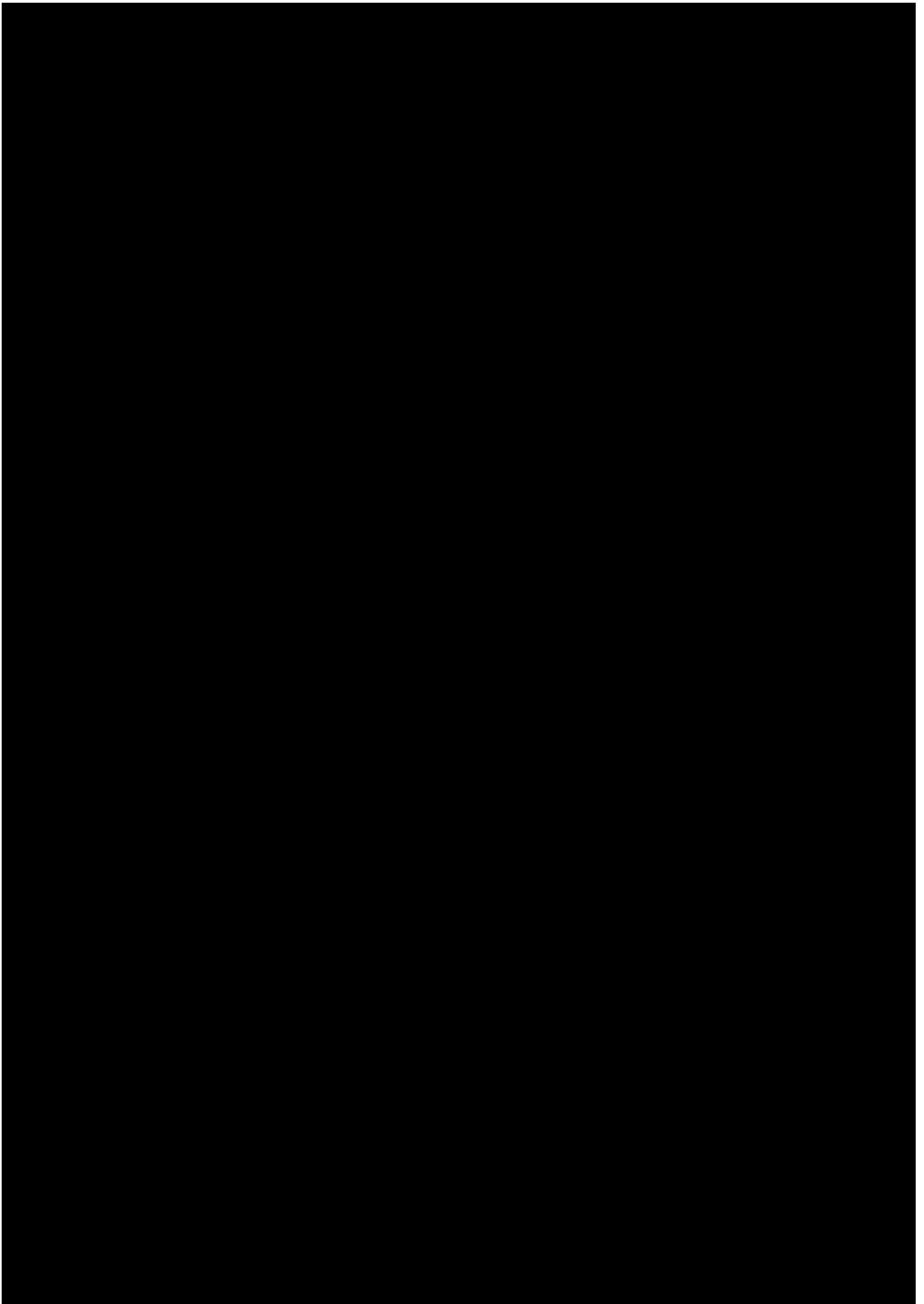
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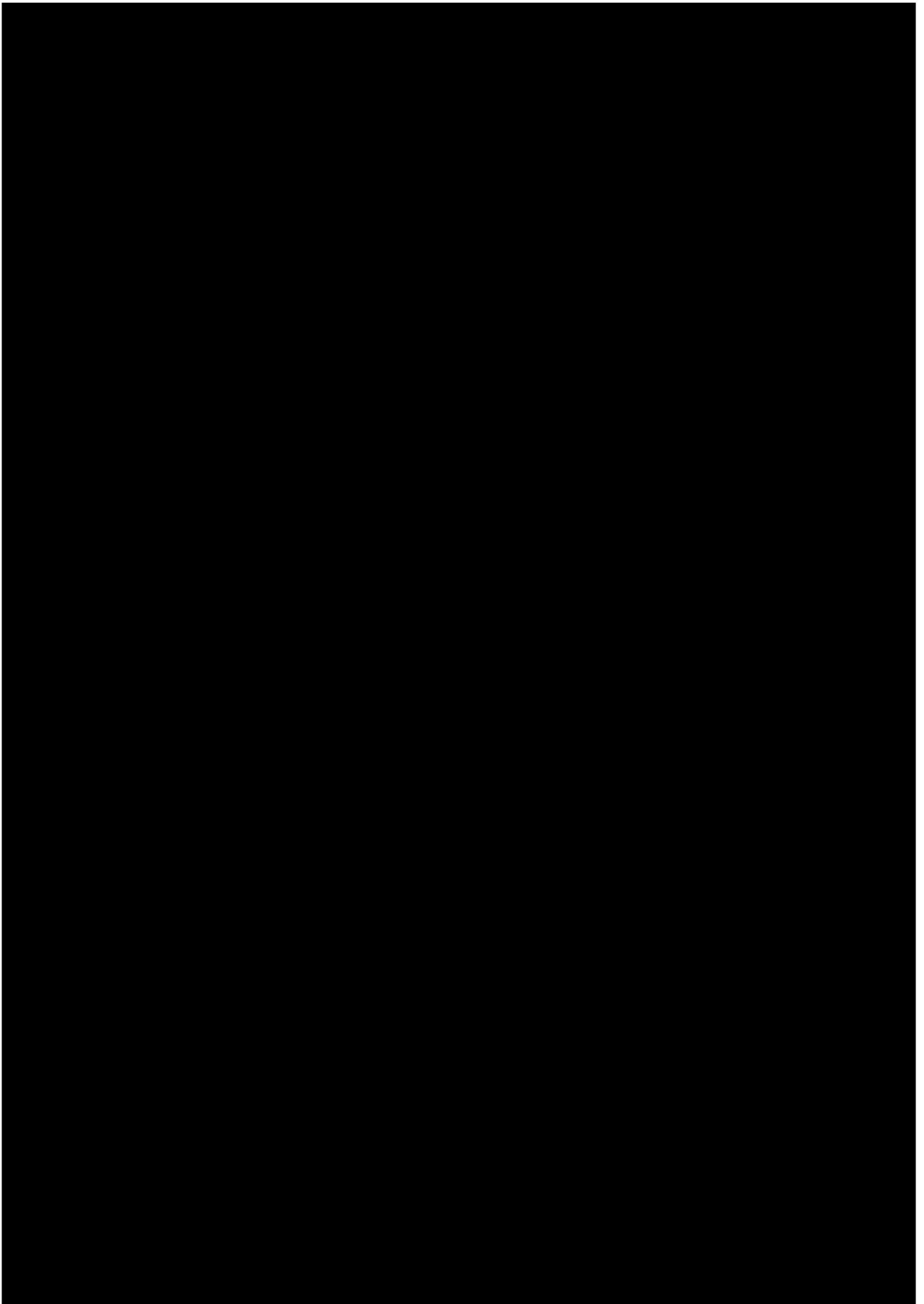




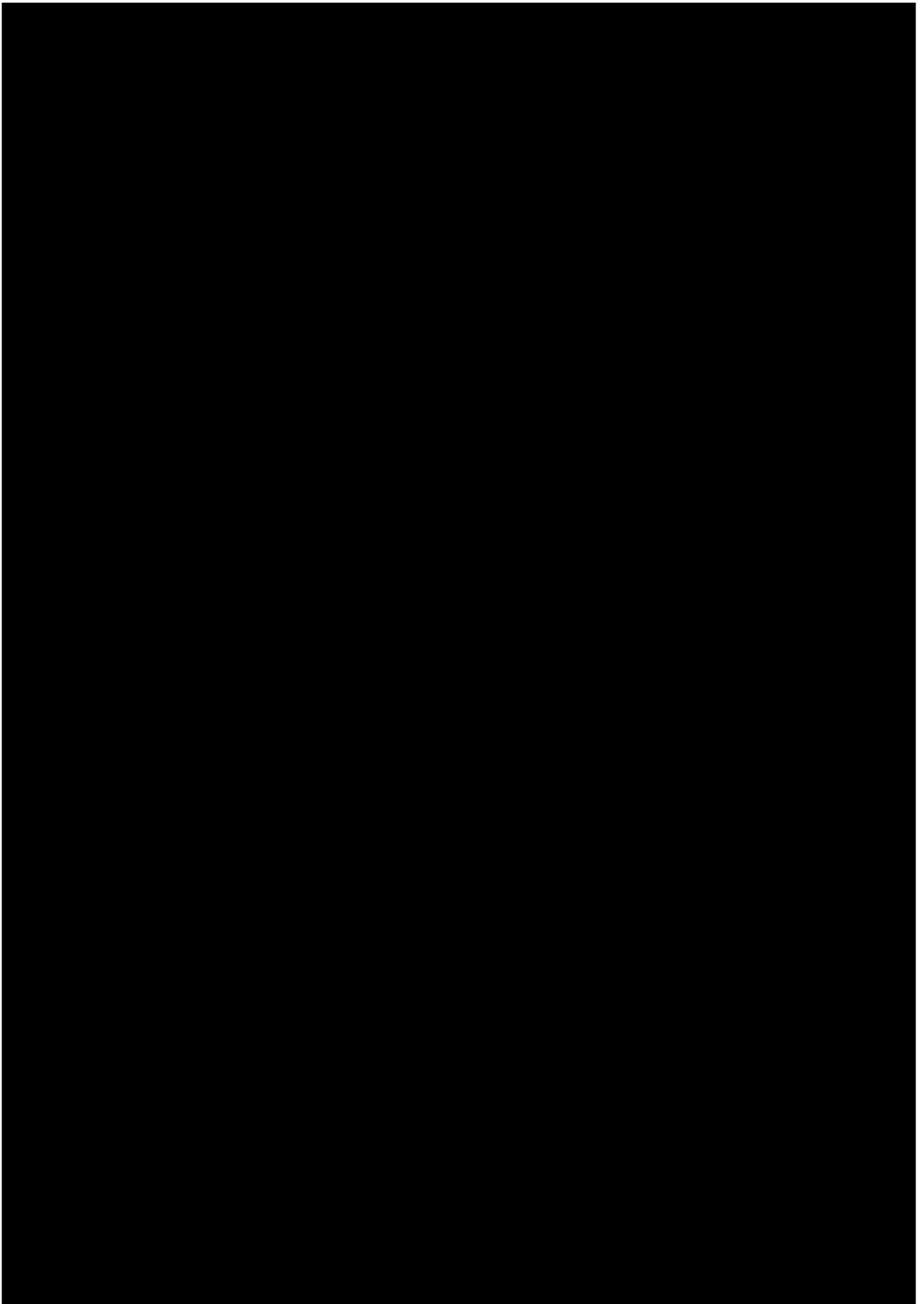


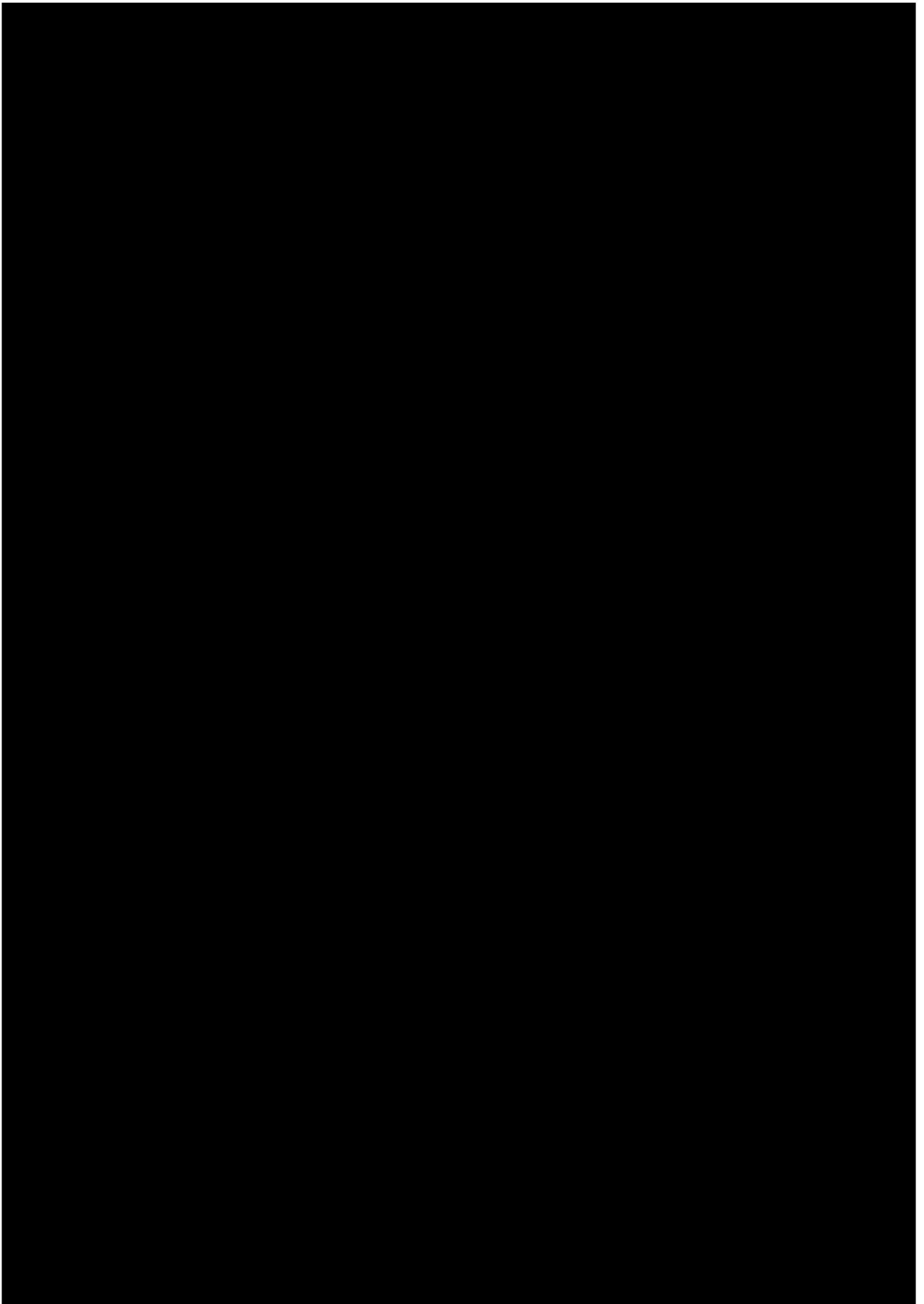


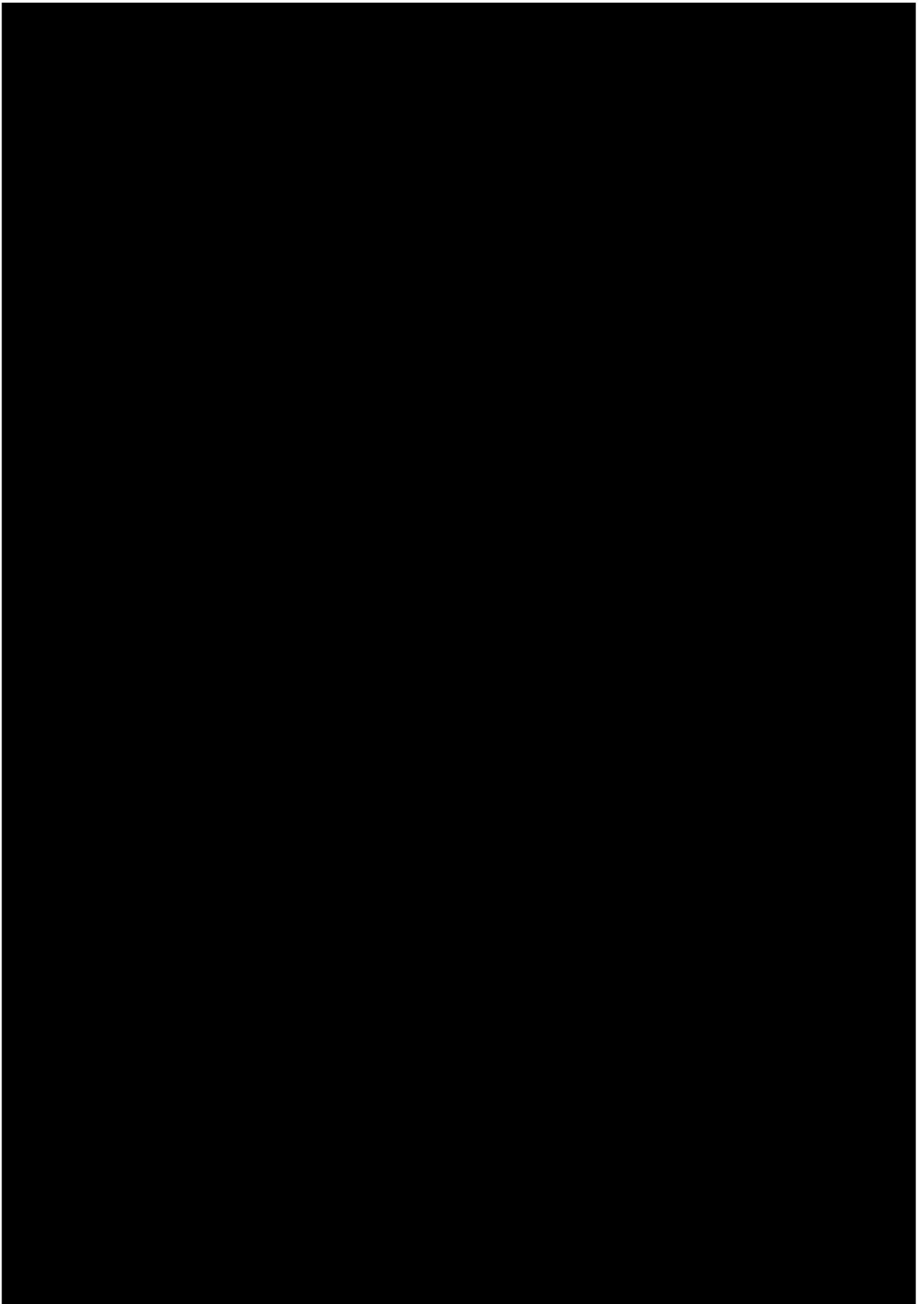


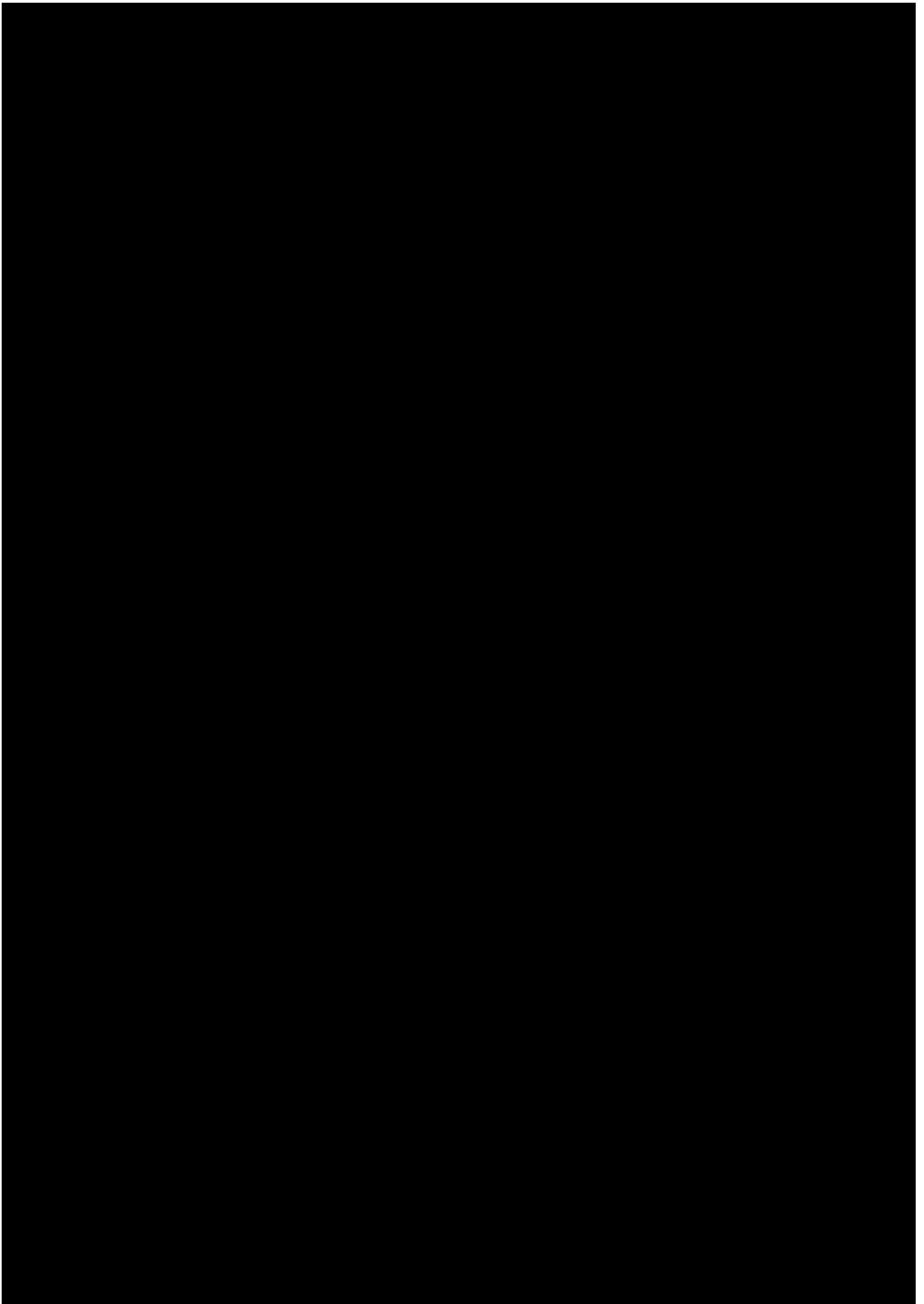


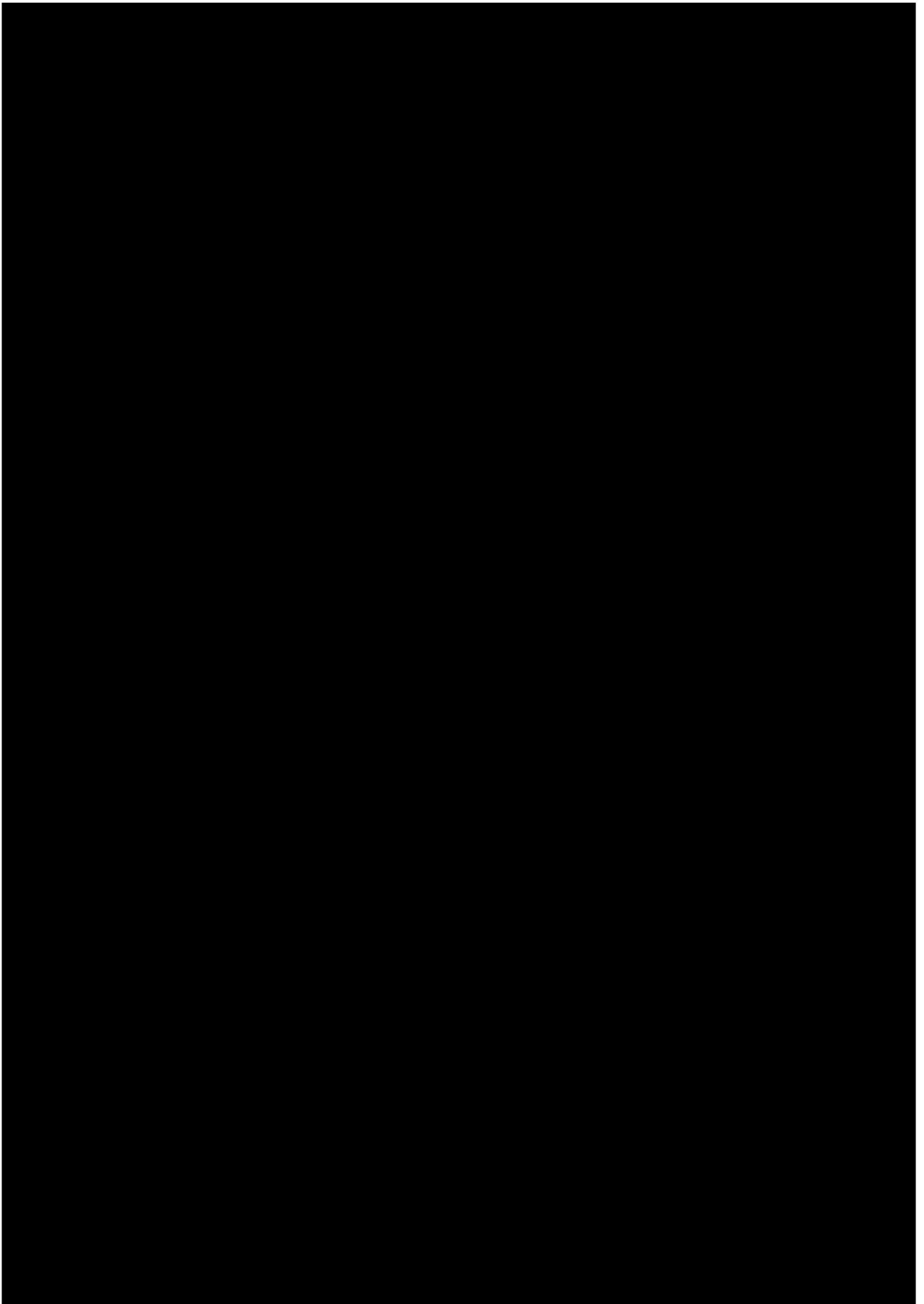
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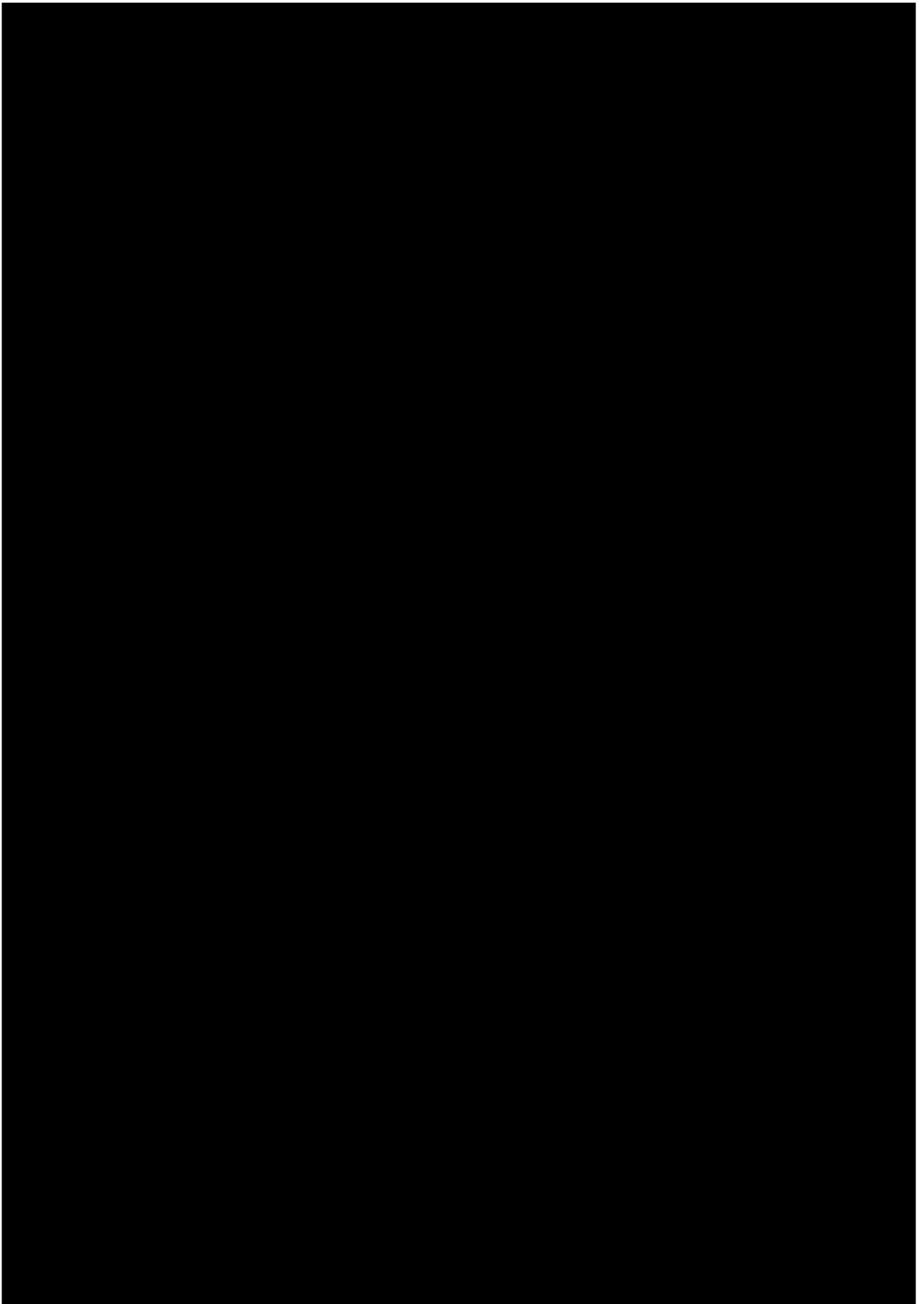


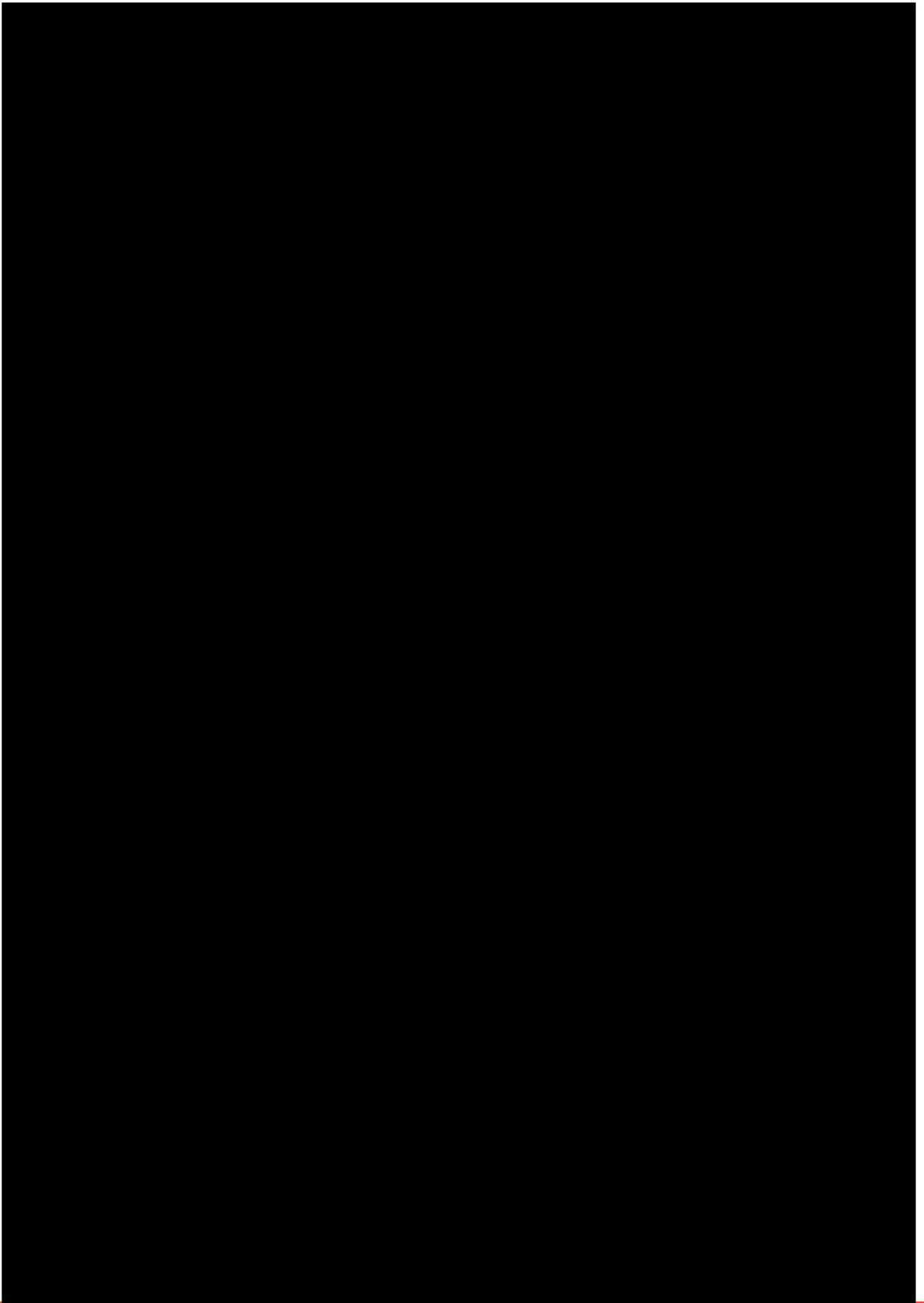


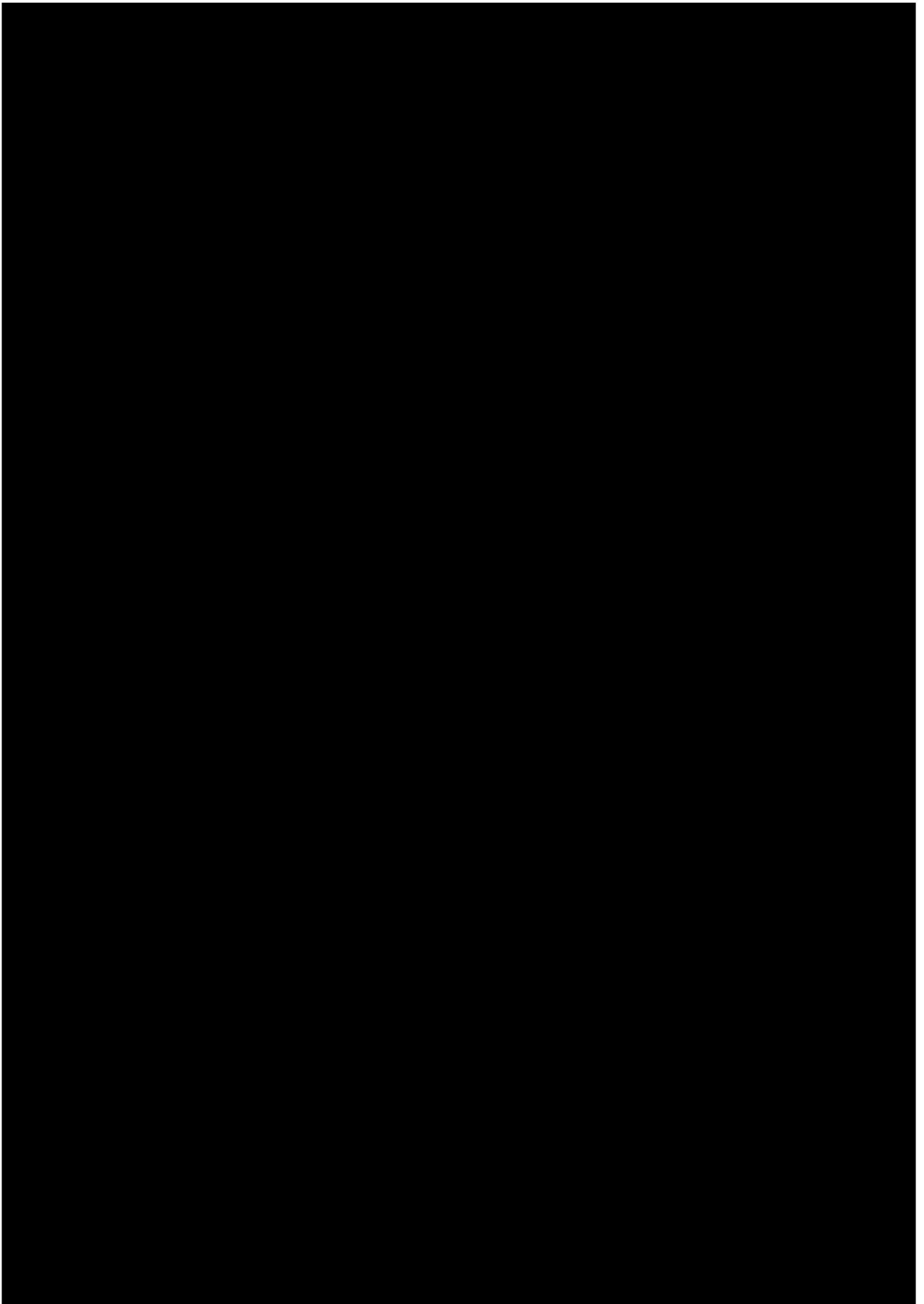


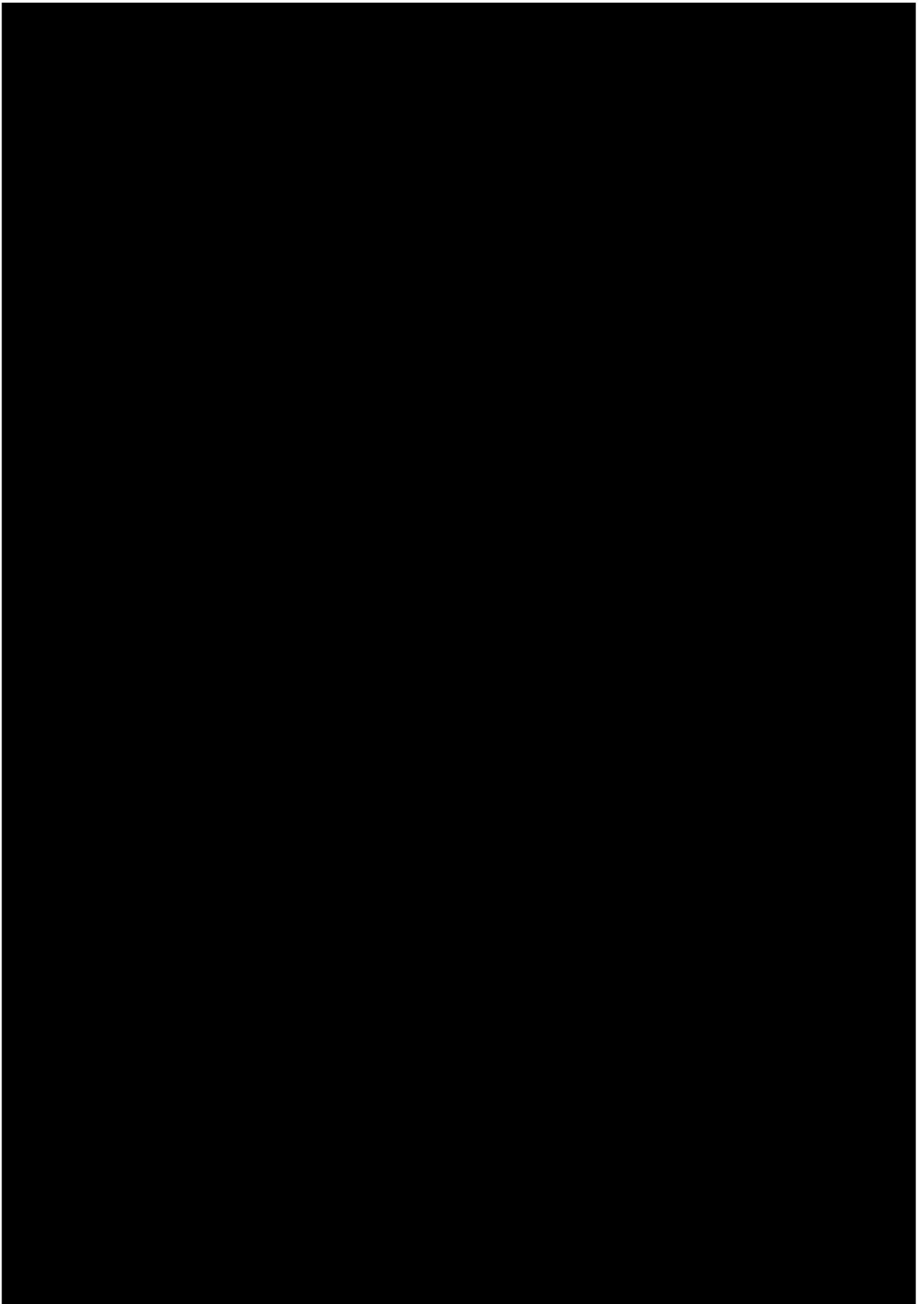


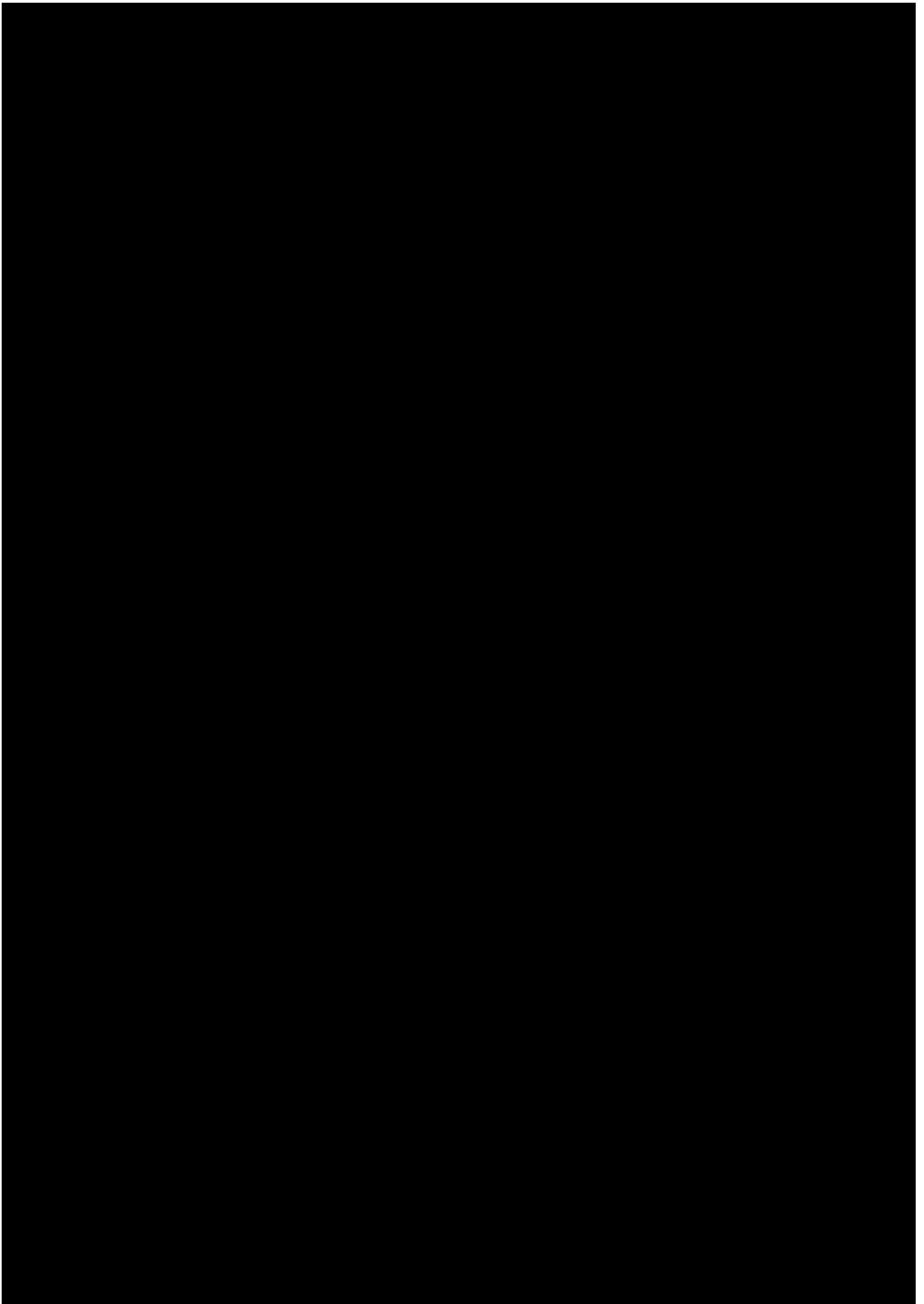


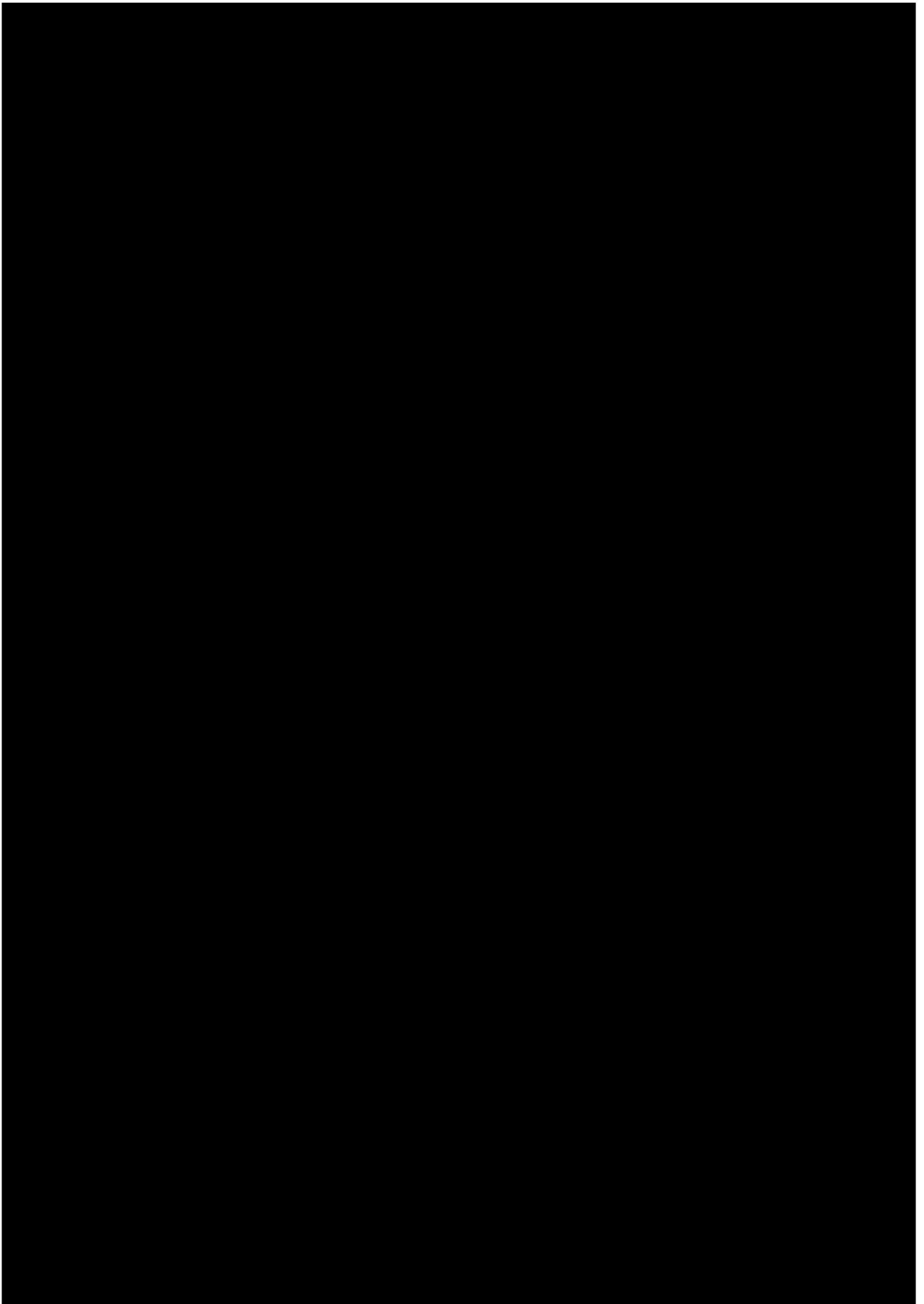


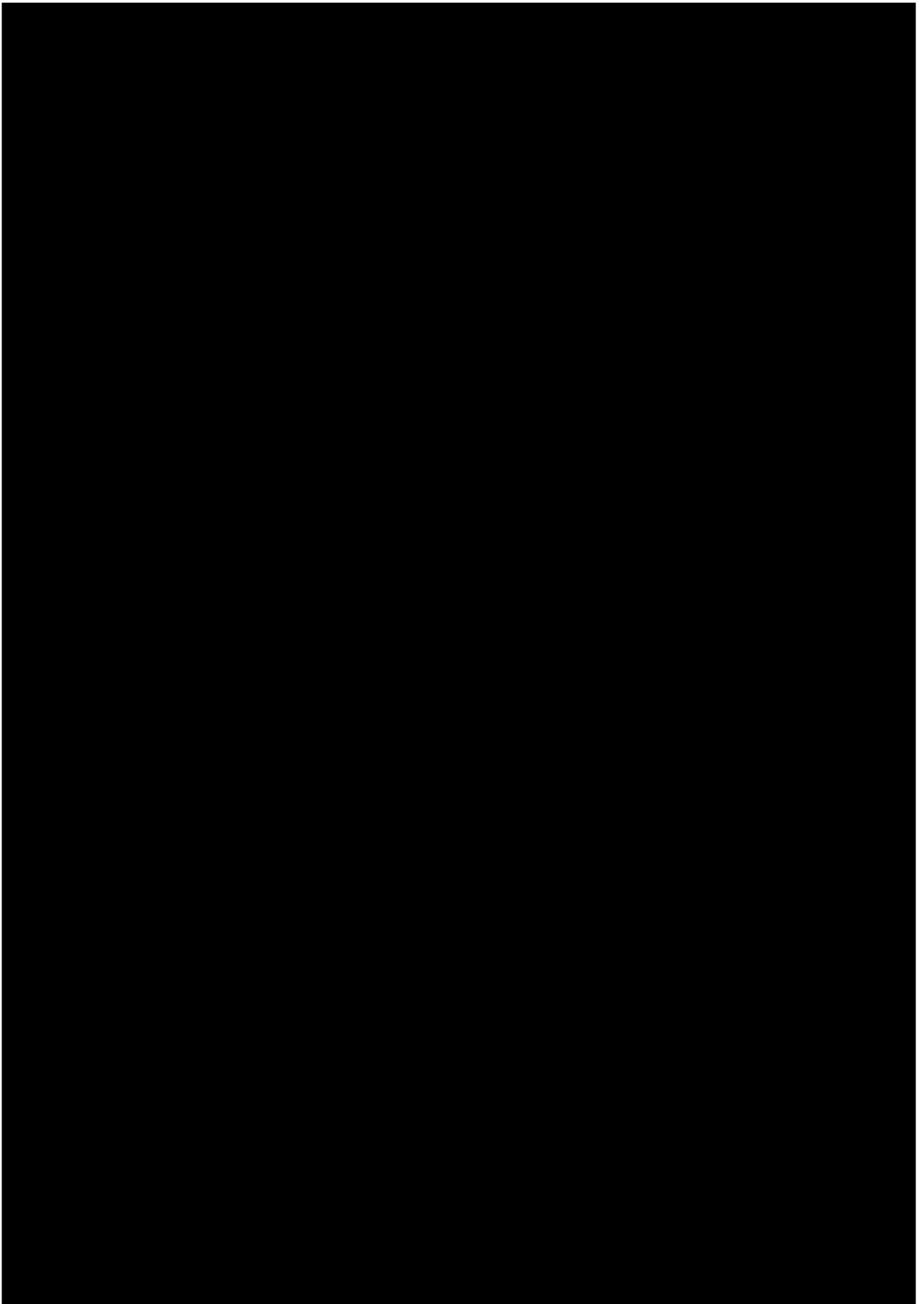


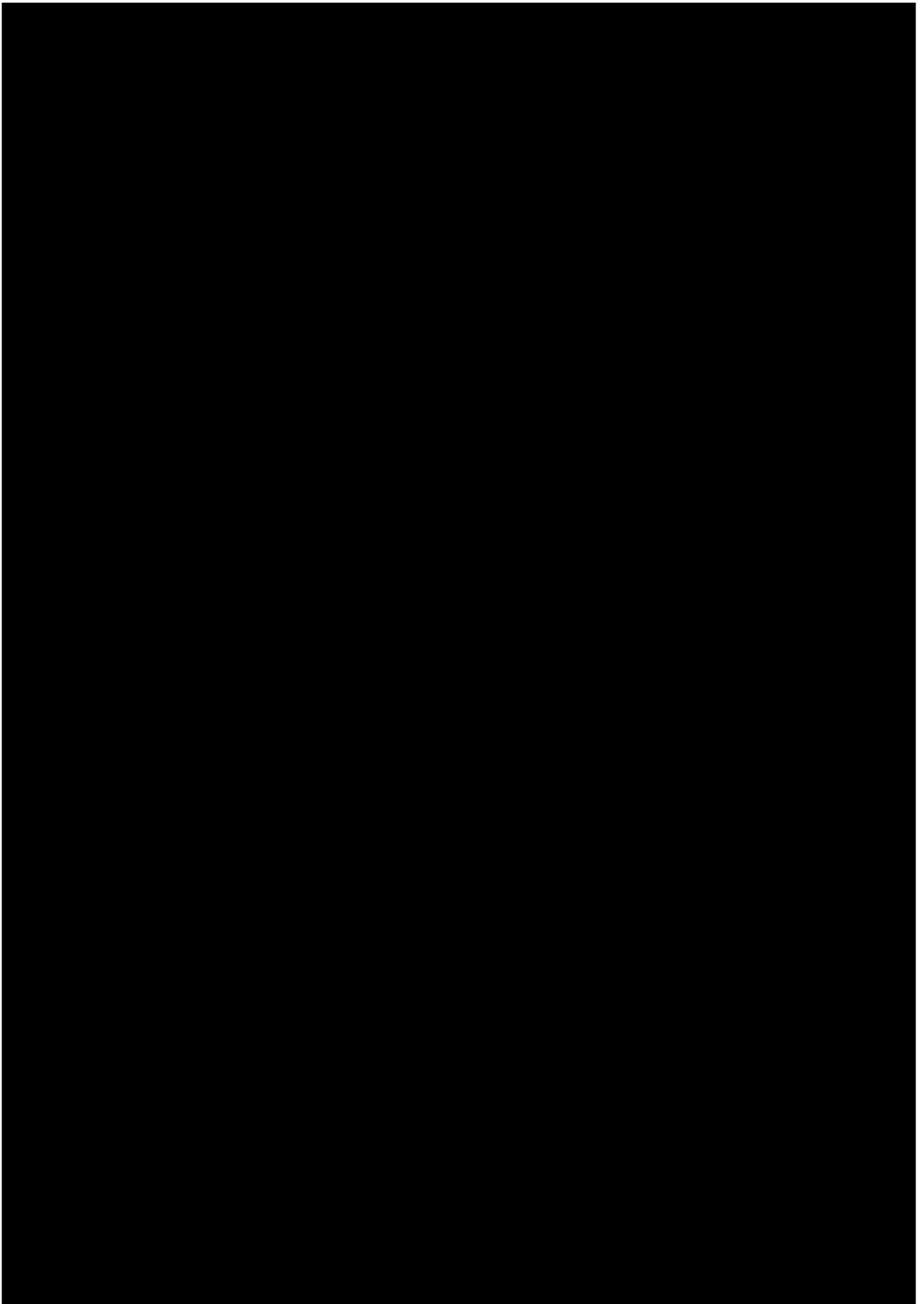


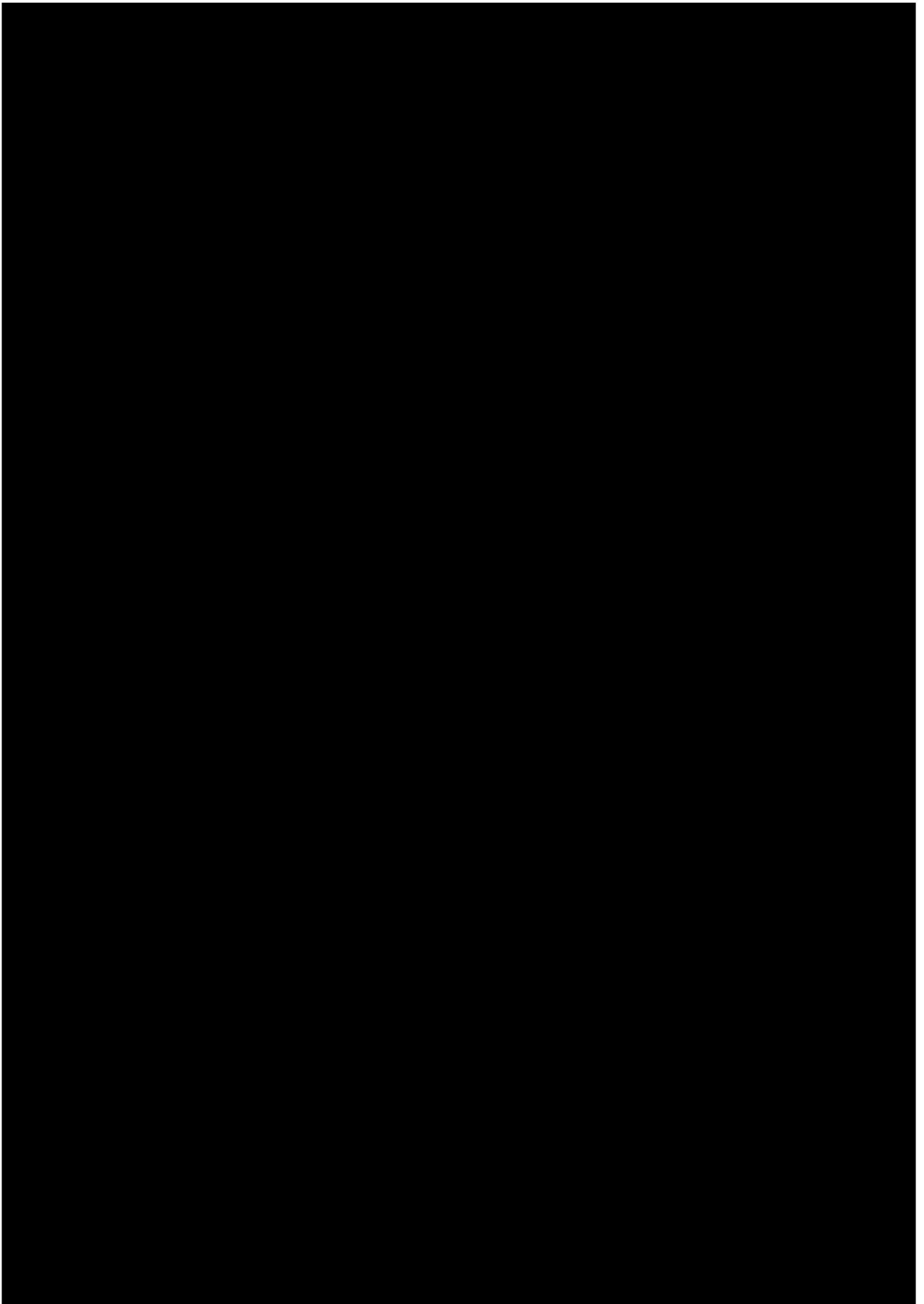


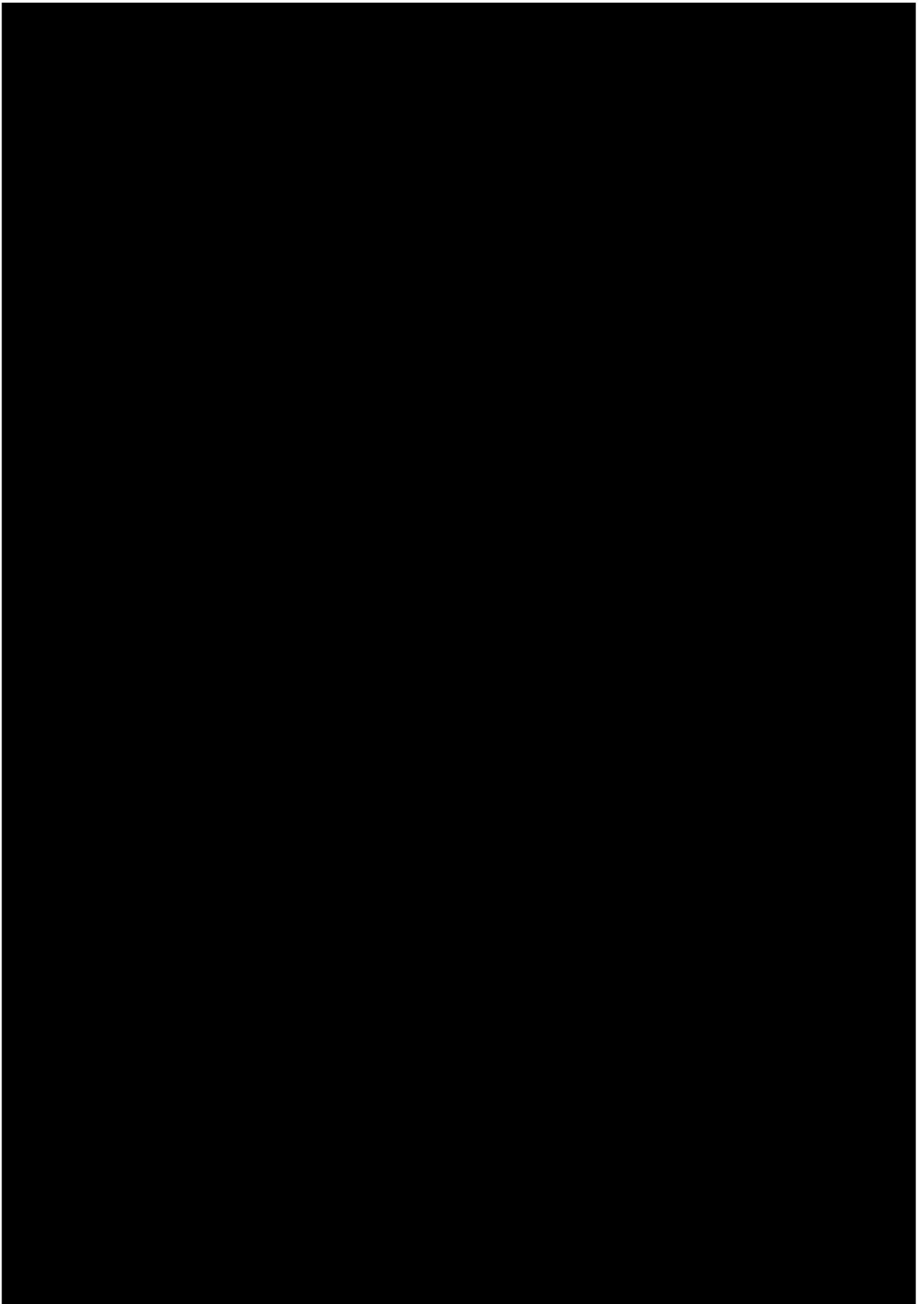












Appendix G: Tennas & King Quantum pro Oxidation Tester



Quantum[®] Pro

Oxidation Tester

ASTM D2272, D2112, D4742, D7098, IP229

Now Available!



Principle

Oxidation Stability: Test material, placed in a stainless steel pressure chamber, is exposed to oxygen at a specific test temperature and pressure. As the antioxidants are consumed, the sample reacts with the oxygen and the pressure drops.

History

Hot oil baths of varying sizes have long been used in the industry for running the Rotating Pressure Vessel Oxidation Test (RPVOT, formerly known as RBOT) and the Thin-Film Oxygen Uptake test (TFOUT). These bath types expose the operator to hot oil fumes and odors, are prone to leak, need regular maintenance, and are generally messy and potentially hazardous to operate.

As laboratory facilities strive to improve their workplace conditions and encourage healthy environments, alternative approaches to running these tests are necessary.

Innovation

Tannas Co. sets a higher standard by eliminating the hazards and mess of hot oil baths. The Quantum[®] Pro Oxidation Tester is **the sole source of supply for ASTM D2272** when running critical oxidation tests. Our technology is simple, clean, and efficient.

Features

- Front-loading, easily accessible pressure chamber.
- Small, bench-top footprint. No laptop or PC required.
- Non-liquid 'Dry-Cylinder' sample heating — eliminates hot, hazardous, liquid bath mess and odor.
- Automated fill and purge control.
- Integrated controls and data acquisition with touchscreen interface.
- Onboard test data storage.
- Integrated Water Calibration.
- Live graph of test data.
- LED lighting scheme based on operating condition.
- Closed loop motor speed control (no calibration required).
- Lower power usage (20 - 30%).
- Lower heat loss, improving external instrument temperature.
- USB ports to transfer records to flash drive or PC.
- Automated test report submission over Ethernet (full or restricted network).

ASTM D2272, D2112, IP229

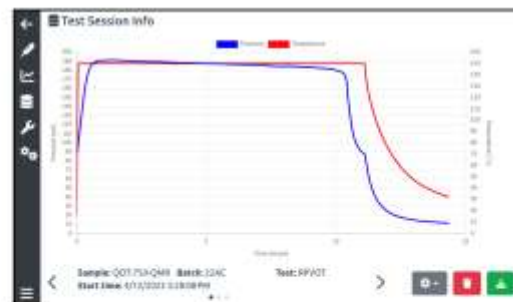
RPVOT: Rotating Pressure Vessel Oxidation Test

ASTM D4742, D7098

TFOUT: Thin Film Oxygen Uptake Test

Common Applications

- Steam Turbine Oils
- New & In-Service Oils
- Insulating Oils
- Gasoline Engine Oils



HMI Touchscreen Interface



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Instrument & Parts

ASTM D2272 & D2112 (RPVOT):

- 200853: RPVOT Sample Beaker
- 200651: Copper Catalyst Coils
- 200910: Magnetic Sample Cup w/ Spring Clip
- 200480: Magnetic Sample Cup Tester
- 200035: Sample Extraction Device Assembly
- 040028: QMR Reference Oil (D2272 only)
- 040027: QHR Reference Oil (D2272 only)

ASTM D4742 & D7098 (TFOUT):

- 200104: TFOUT Conversion Package
- 200106: TFOUT Segmented Glass Dish
- 010047: TFOUT Catalyst A Package
- 010049: TFOUT Catalyst B Package

All Applications:

- 200916: Oxygen Regulator
- 200914: Certified Reference Oxygen Gauge
- 040045: VarClean Cleaner

Instrument Specifications

Dimensions	23(w) x 50(d) x 41(h) cm (9 x 19.65 x 16 in)
Weight	~ 15.9 kg (35 lbs.)
Voltage	100-240 VAC
Frequency	50/60 Hz.
Heating Medium	Dry Cylinder heating system - no hot oil bath
Testing Capacity	Single position stainless steel pressure vessel Designed for multi-unit alignment, each independent
Test Parameter Capabilities	Temperature: 160° ± 0.1°C recommended max. Oxygen Charge: 100 ± 0.1 psi recommended max. Vessel Rotation: Variable speed control
Output	Continuous temperature & oxygen pressure readout
Safety	Auto-Shutoff at end of test Current limiting fuses Over-pressure sensor & relief Over-temperature cutoff fuse CRN Approved & CE Marked Manual fill and purge control
Shipping Weight & Dimensions	~26 kg (58 lbs.) approx. ~53 x 46 x 58 cm (21 x 18 x 23 inches) approx.

Additional TANNAS CO. Precision Laboratory Instruments

Tannas Foam Air Bath (TFAB)

- ASTM D892, D6082, D1881, D7840, IP146
- Non-liquid bath
- 24°C to 150°C range

TBS 3000 HTHS Viscometer

- ASTM D4683, D6616, CEC L-36, IP370
- High-Temperature, High-Shear (HTHS)
- 80°C, 100°C, 150°C testing

Noack 52" Volatility Test

- ASTM D5800, Procedure D, CEC L-40
- Phosphorus Volatility
- Non-Wood's metal heating system

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Appendix H: Inficon Extrima Calibration Manual & Example Certificate



Calibration Leaks



The easy way to calibrate hydrogen leak detectors

Leak testing is a matter of quantifying leaks. To be able to correctly accept/reject test objects you need to measure to a set standard. You also need to calibrate your leak detector against a reliable reference leak. INFICON calibration leaks for hydrogen leak detectors cover a wide range of leak rates to suit your specific application.

For maximum accuracy, our calibration leaks are equipped with a specially developed diffuser nozzle. This nozzle allows the gas to spread evenly after leaving the leak without variations caused by air convection. The distinctive diffuser holder also eliminates the risk of varying or irregular readings depending on the way the probe approaches the leak. The calibration leaks are designed to suit INFICON Hydrogen Leak Detector Sensistor Sentrac, but can easily be used to calibrate most gas detectors. The INFICON family of calibration leaks for hydrogen leak detectors include bigger leaks

(Types A-C) and smaller leaks (Types E and G). Leak Type A is intended for accumulation testing only. All leaks are traceable to NIST, NMIJ, NPL, PTB, etc., through the "Mutual Recognition Arrangement of the BIPM".

TYPES AND CONNECTIONS A-C

- Sintered stainless steel
- Inlet: Compression connector for 6 x 4 mm and 1/4" x 5/32" tubing. ISO G1/8" internal behind connector
- Outlet: ISO G1/8" external
- Purge valve: Plug to be opened with 2.5 mm Allen key (hex drive). M5 internal behind plug. Fits also UNF10-32

E AND G

- Crimped metal capillary
- Filling connection: 1/4" male NPT, adapter for male ISO 1/4" included

ADVANTAGES AT A GLANCE

- Suitable for industrial applications
- Refillable and simple to use
- Special nozzles included for all INFICON hydrogen leak detector hand probes (not Leak A)
- Traceable to NIST, NMIJ, NPL, PTB
- Certificate included
- Available in different flows
- Suit different concentrations of hydrogen tracer gas



REFERENCE LEAKS

CONTENT AT DELIVERY

Type A

- Calibration leak assembly comprising leak and purge valve assembly
- Red G1/8" gasket
- Collet nut for connection to 1/4" tubing (marked red)
- Calibration certificate
- Delivery and storage case
- Manual

TYPE A



Type B and C

- Calibration leak assembly comprising leak and purge valve assembly
- Diffusor holder (for hand probe calibration)
- Diffusor filter (2 pcs)
- Probe guide rings, 8-11 mm diameter (4 pcs)
- Red G1/8" gasket
- Collet nut for connection to 1/4" tubing (marked red)
- 2.5 mm Allen key (hex drive) for purge valve and assembly of diffusor
- Calibration certificate
- Delivery and storage case
- Manual

TYPE B AND C



Type E and G

- Reference leak assembly
- Thread adapter (1/4" NPT- 1/4" ISO)
- Diffusor holder (for hand probe calibration)
- Diffusor filter (2pcs)
- Probe guide rings, 8-11 mm diameter (4 pcs)
- 2.5 mm Allen key (hex drive) for assembly of diffusor
- Calibration certificate

TYPE E AND G



SPECIFICATIONS AND ORDERING INFORMATION

Target flow for standard leaks:

Type	Part no.	Nominal flow** atm ml/s	Accuracy	Equivalent to g/yr (R134a)	For equivalent flow in: mbaL/s or atm cc/s (air)	mbaL/s or atm cc/s (5% H_2 /95% N_2)
A*	590-420	5×10^{-1} (Air)	$\pm 2\%$		multiply with 1	multiply with 1.04
B	590-421	5×10^{-1} (Air)	$\pm 2\%$		multiply with 1	multiply with 1.04
C	590-422	5×10^{-1} (Air)	$\pm 2\%$		multiply with 1	multiply with 1.04
E	590-427	7×10^{-1} (5% H_2 /95% N_2)	$\pm 10\%$	10	multiply with 0.96	multiply with 1
G	590-429	2×10^{-1} (5% H_2 /95% N_2)	$\pm 10\%$	3	multiply with 0.96	multiply with 1

A-C leaks are certified at 1 bar pressure, E and G leaks shall be pressurized according to certificate.

*Type A leaks are delivered without diffuser nozzle and are recommended for accumulation testing only. They can not be used for calibrating hand probes with 5% H_2 / 95% N_2 .

**A-C leaks are delivered with leak size within $\pm 10\%$ of nominal flow, E and G leaks with leak size within $\pm 25\%$ of nominal flow.



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Due to our continuing program of product improvements, specifications are subject to change without notice.
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SG8 7SL, UK
T: +44 (0)1763 208503
E: info@ionscience.com
ionscience.com

CALIBRATION CERTIFICATE

Date of Calibration: - 20th October 2023

Calibrated by: - C Payne

Customer: - Inficon AB

Description: - Standard Calibrated Leak

Manufacturer: - ION Science Ltd

Type Number: - SCL

Serial Number: - SCL4844

Certificate Number: - 267558

Signed:

Calibration Due Date: - October 2024

This instrument has been factory calibrated to fully documented procedures in accordance with our ISO 9001:2015 Quality Management System.
Measurement standards are derived from volumetric and time sources which have been calibrated at an accredited laboratory traceable to National or International standards. The following list indicates the serial numbers of equipment used during the calibration procedure.

BARGS	SCL01	D601	FLOW/IS06		
-------	-------	------	-----------	--	--

The instrument has been calibrated at a temperature of 20.7°C ± 0.25°C and a barometric pressure of 972.6 mbar ± 2 mbar.

ION Science hereby certify that on the day of calibration the instrument was working according to the manufacturer's original sales specification as checked by the calibration procedure, unless otherwise stated.

Copies of this certificate may only be reproduced in full.

Calibrations are valid as certified only on date of calibration.

RESULTS ON DESPATCH

Applied Pressure	Measured Flow
1 BarG Air	5.3 ± 10% mV/sec

The estimated measurement uncertainty is ± 2.0%

Comments: -

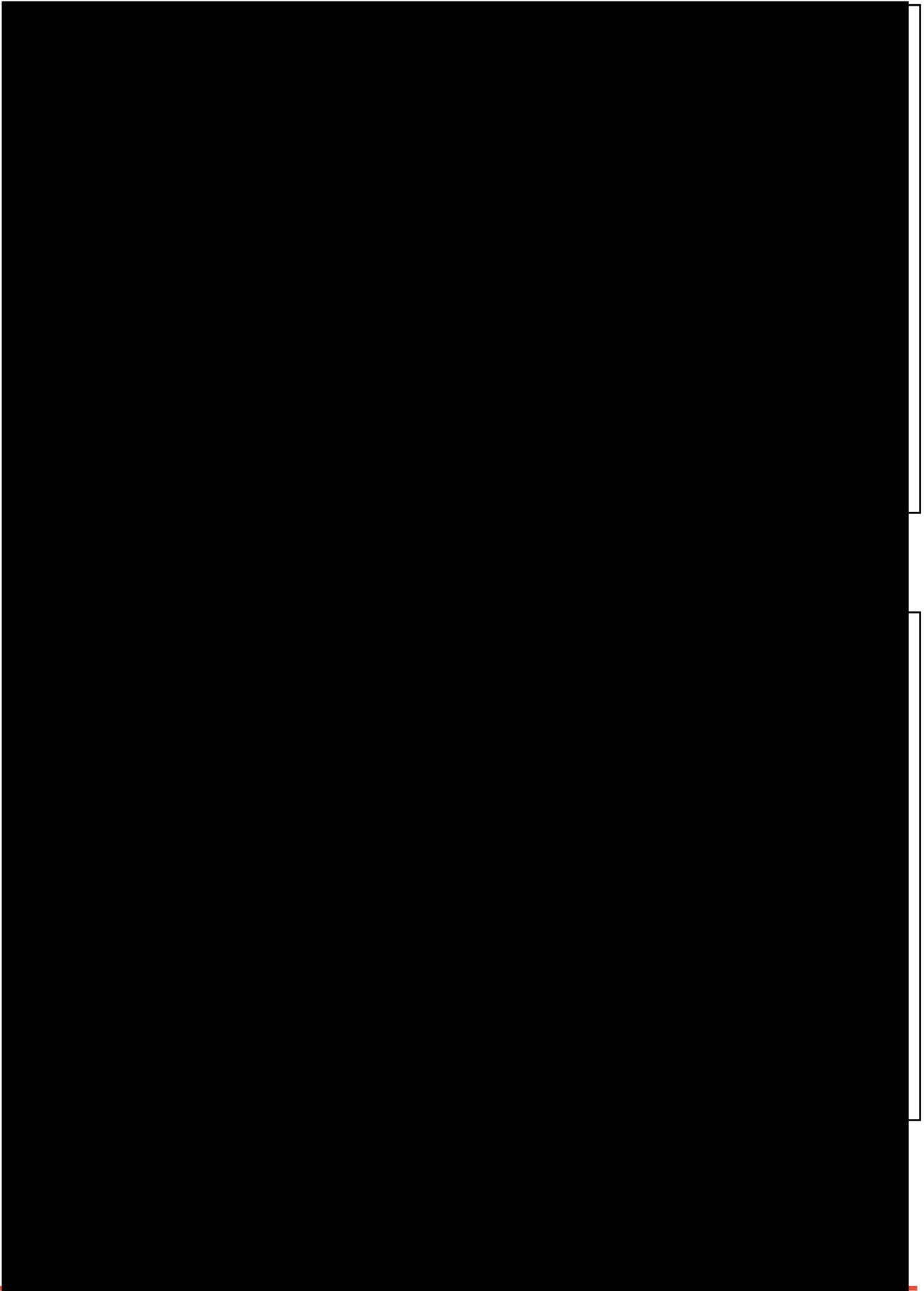
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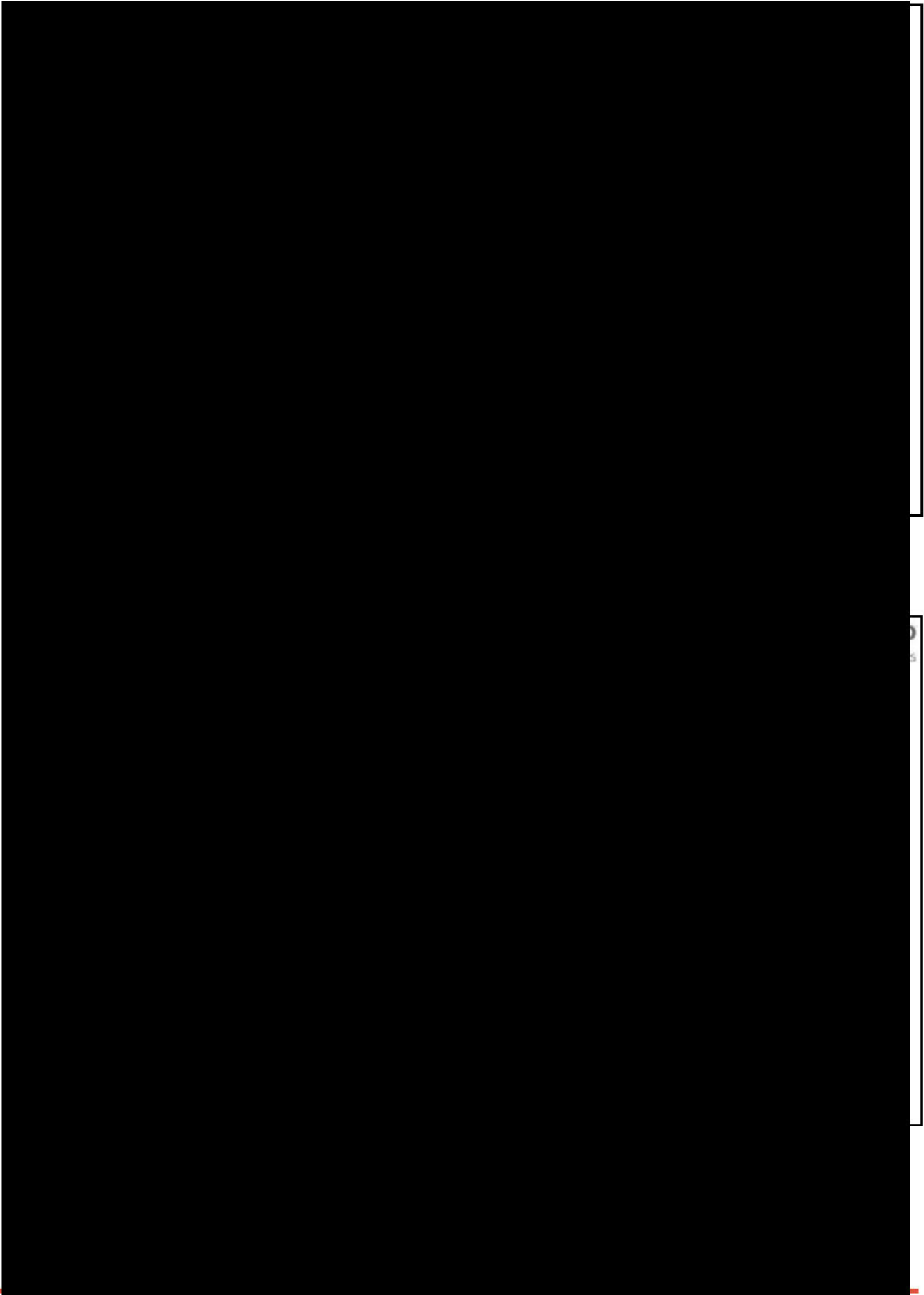
Pioneering Gas Sensing Technology.

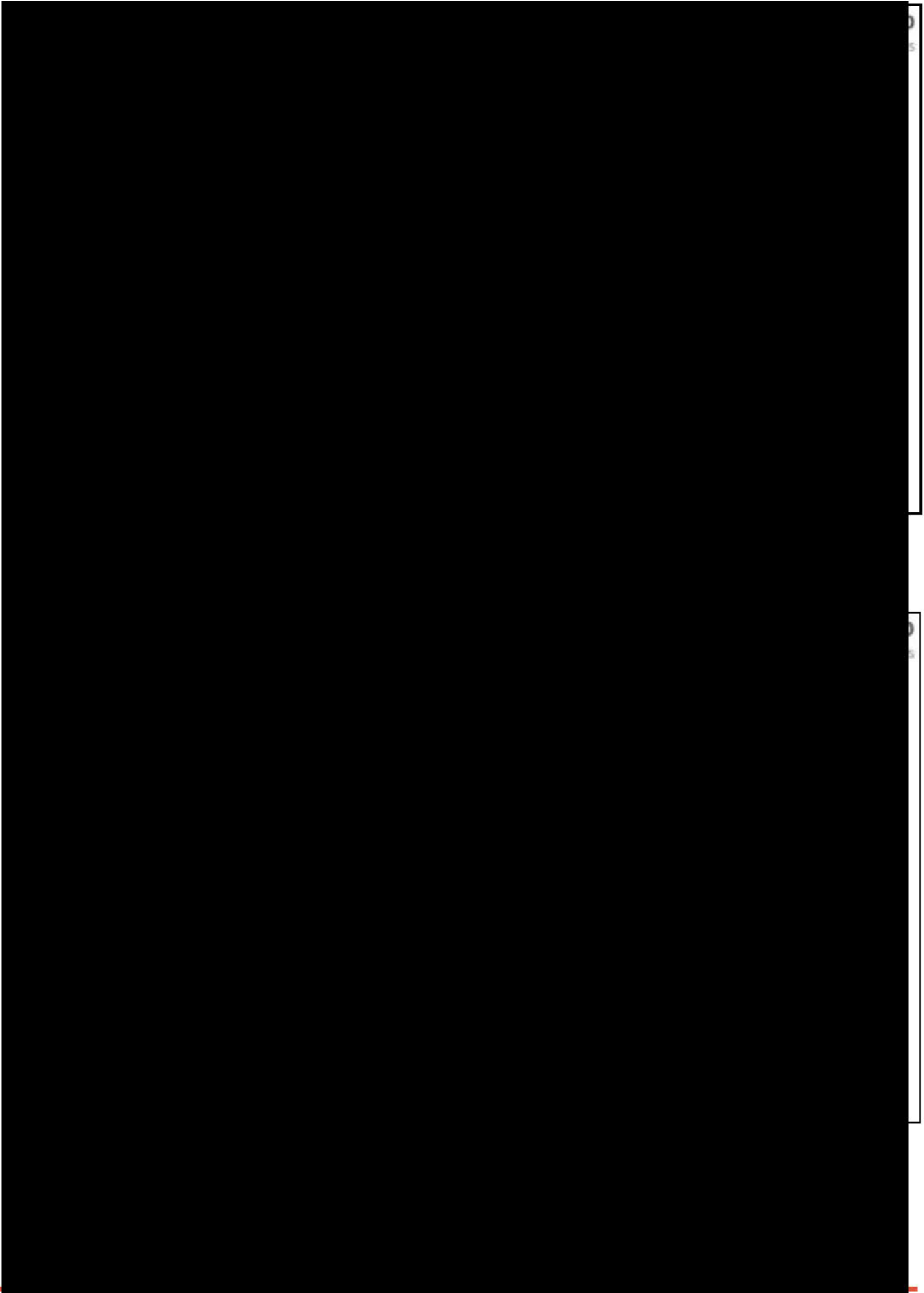
ION Science Ltd
Registered in England No. 2359038 VAT No. GB 532 2024 00

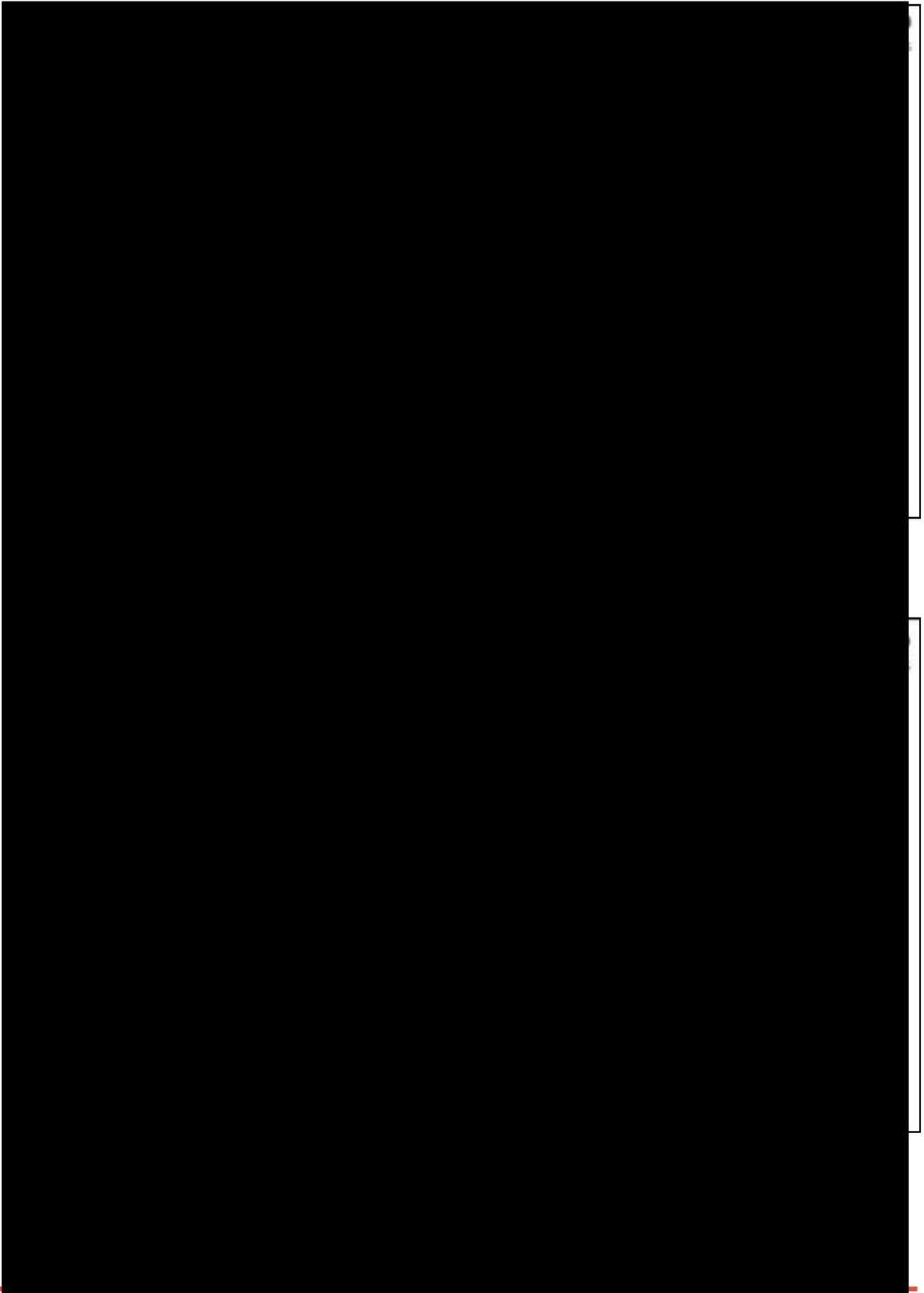


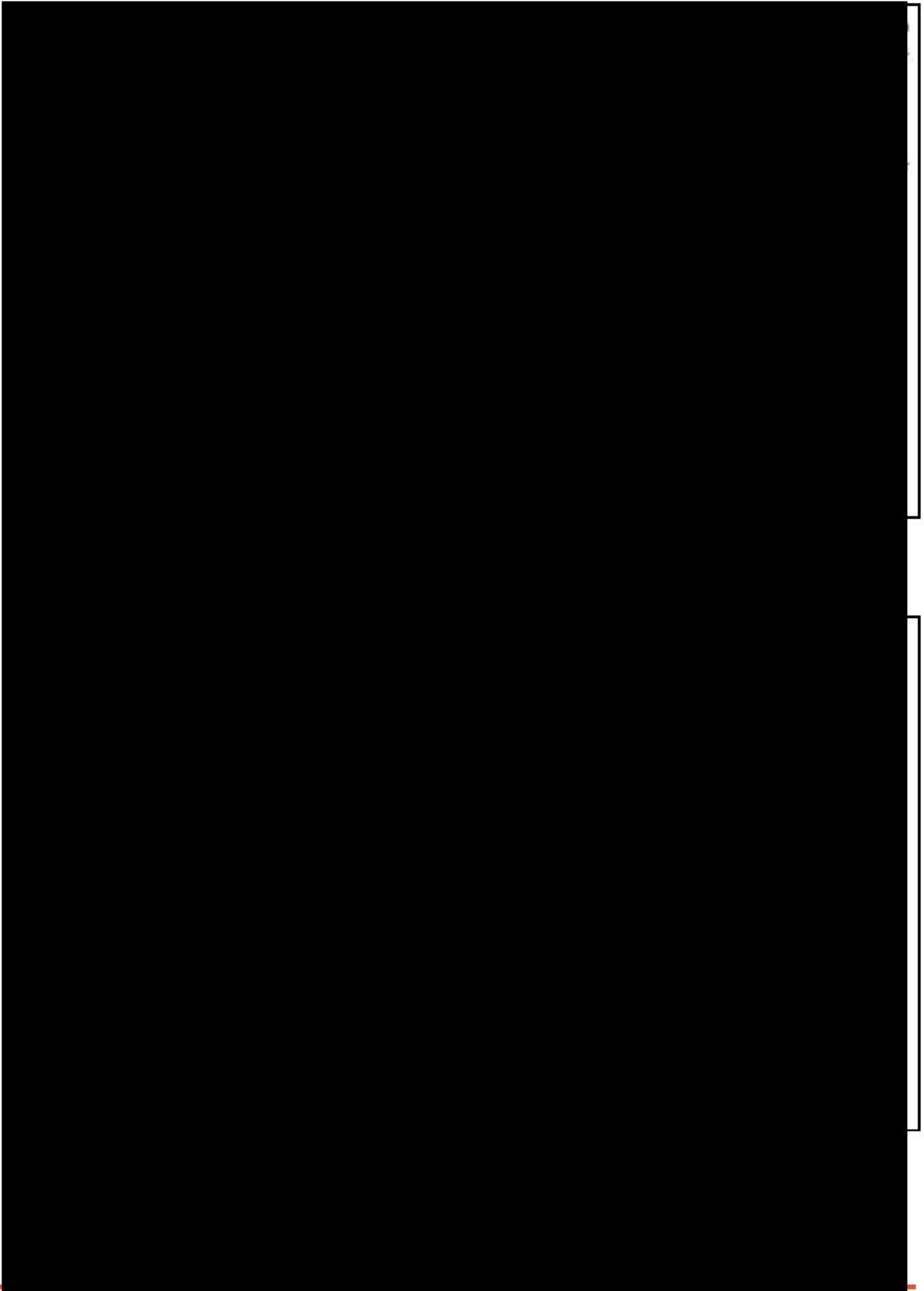
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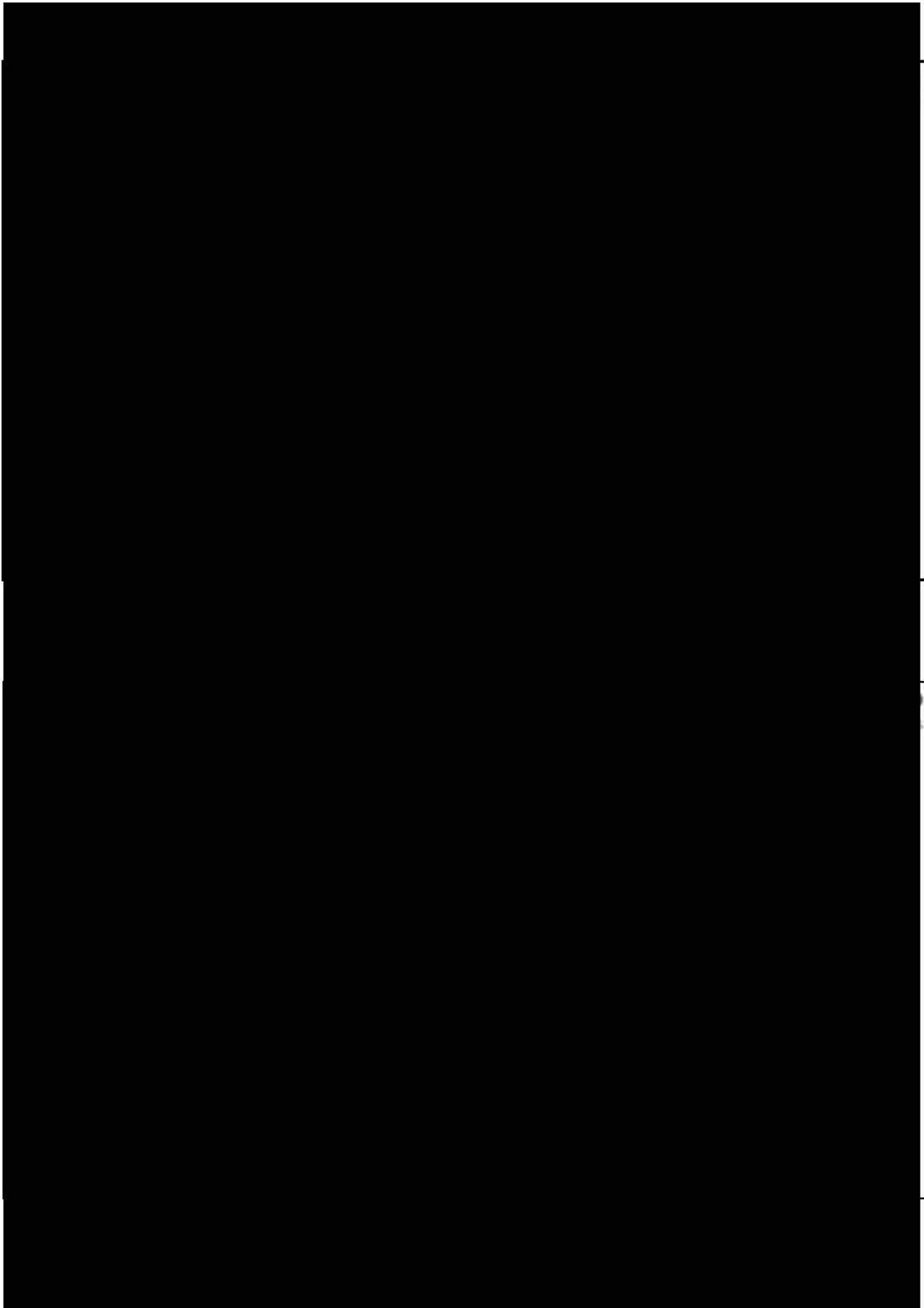


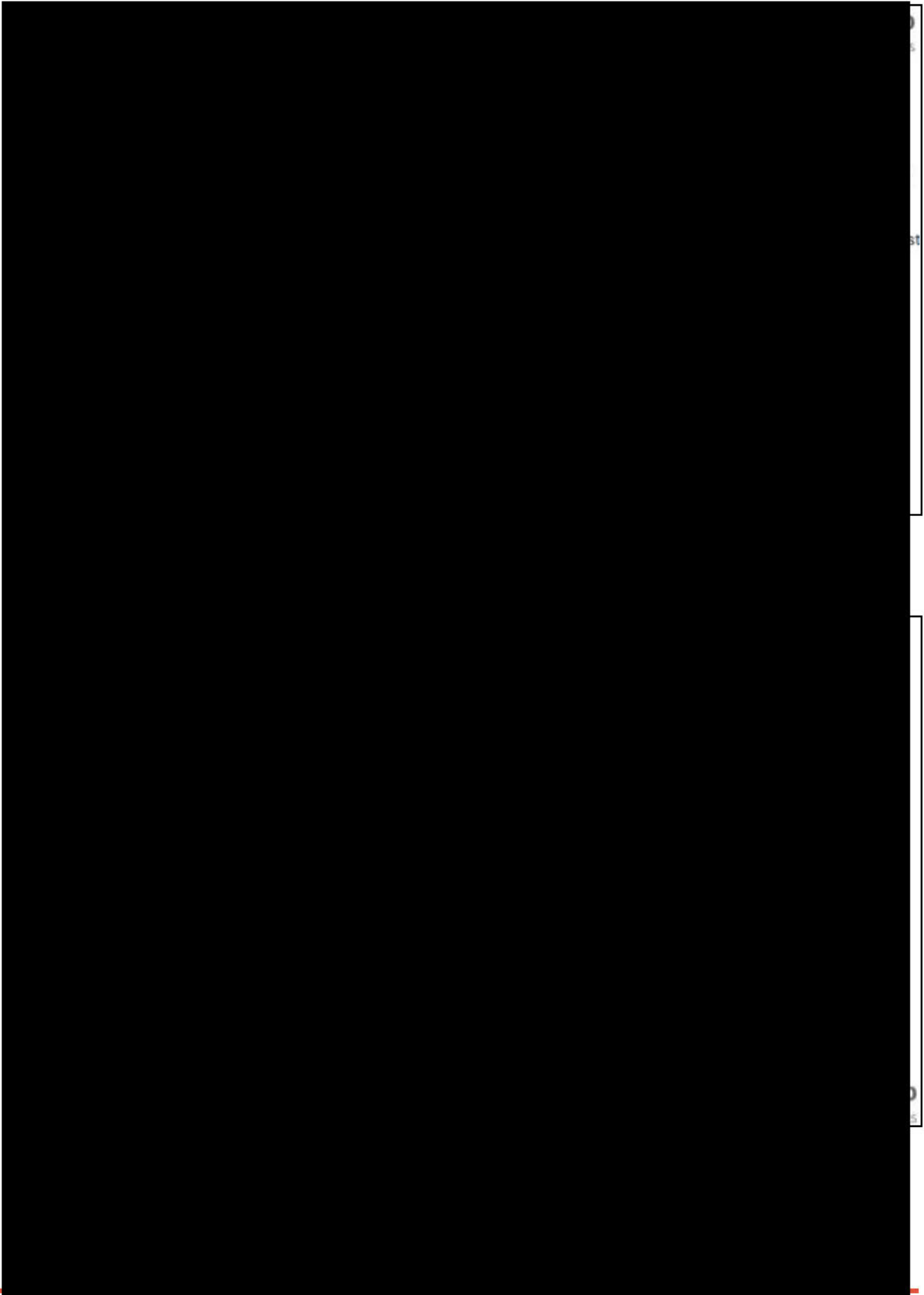


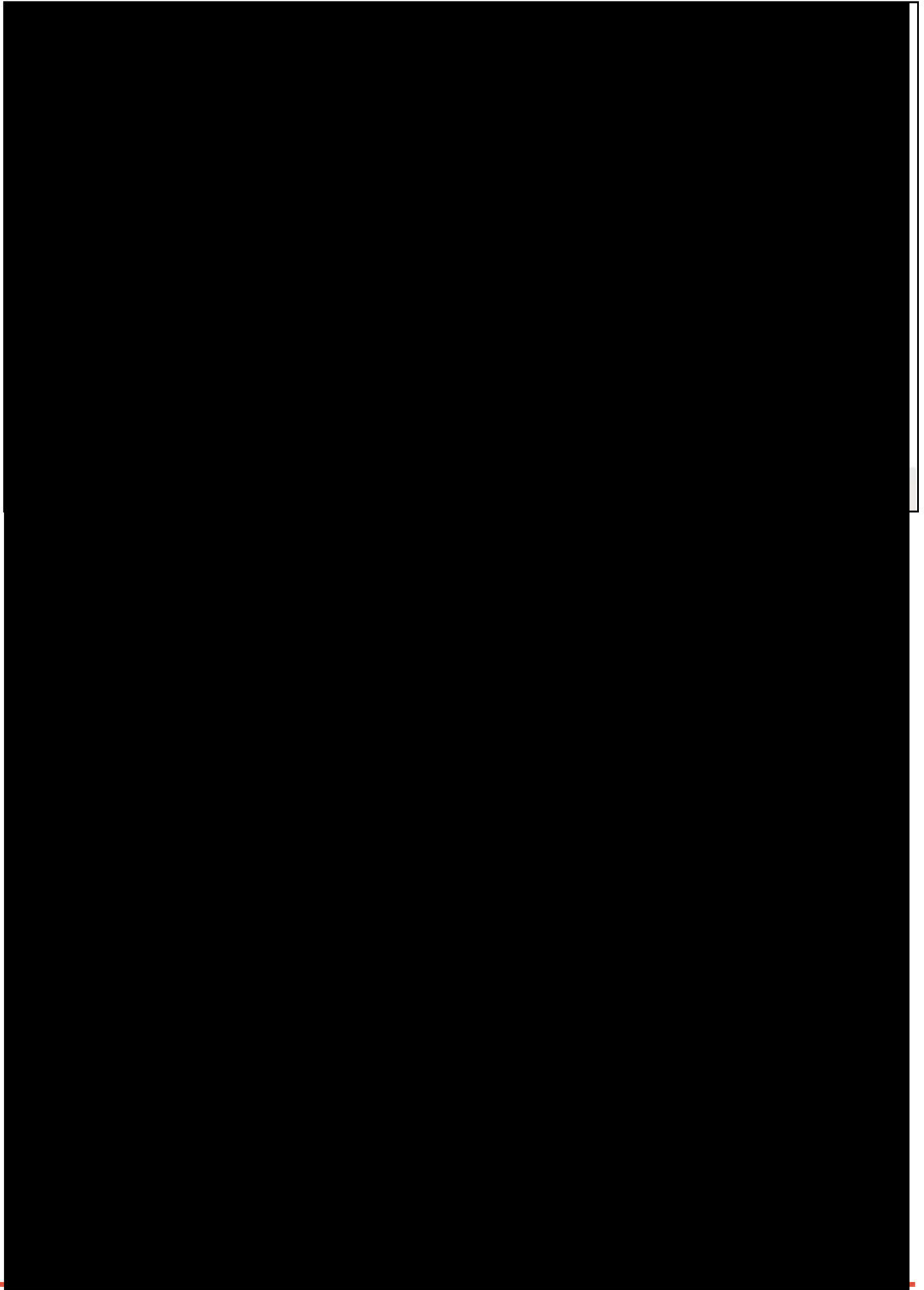




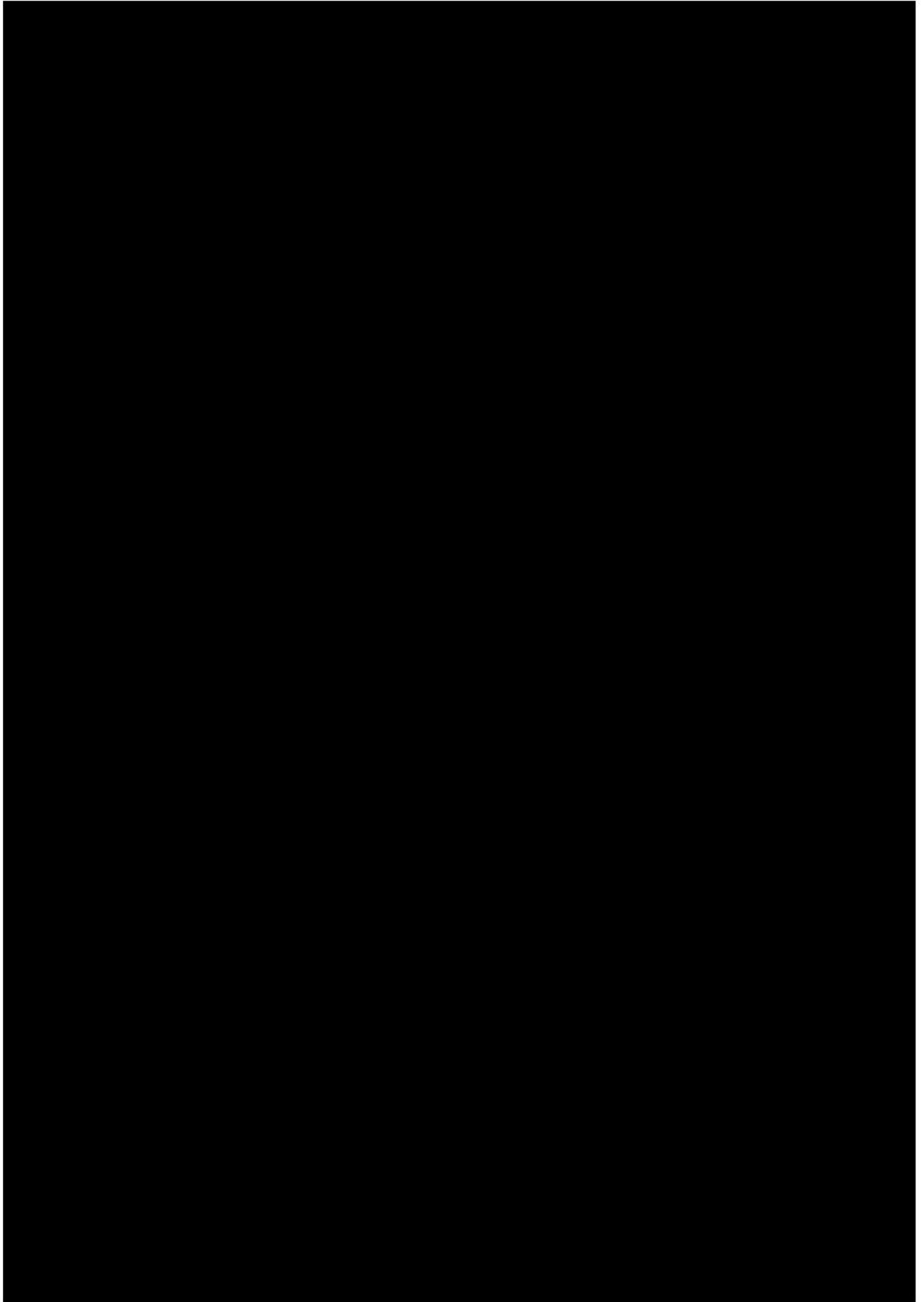


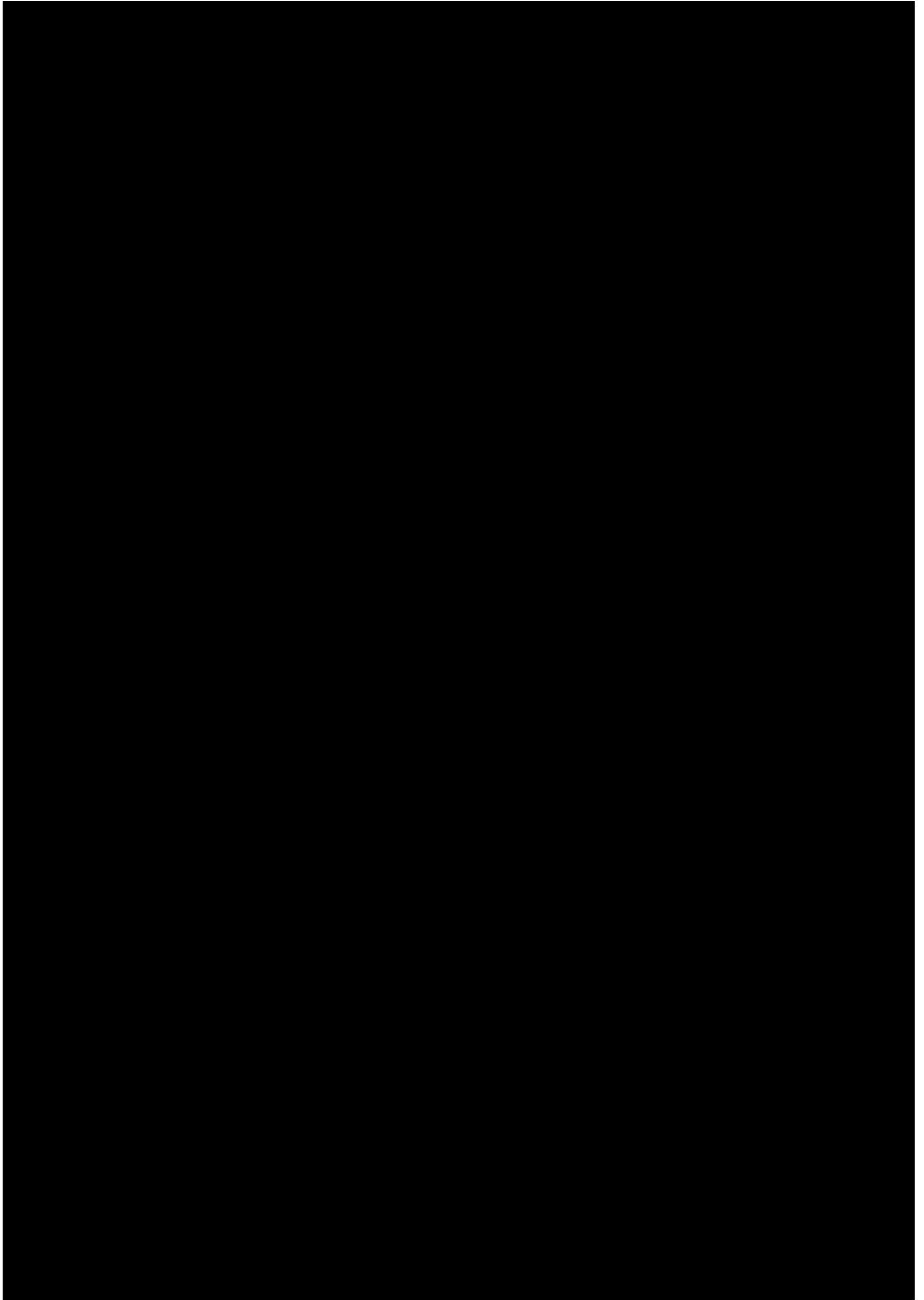


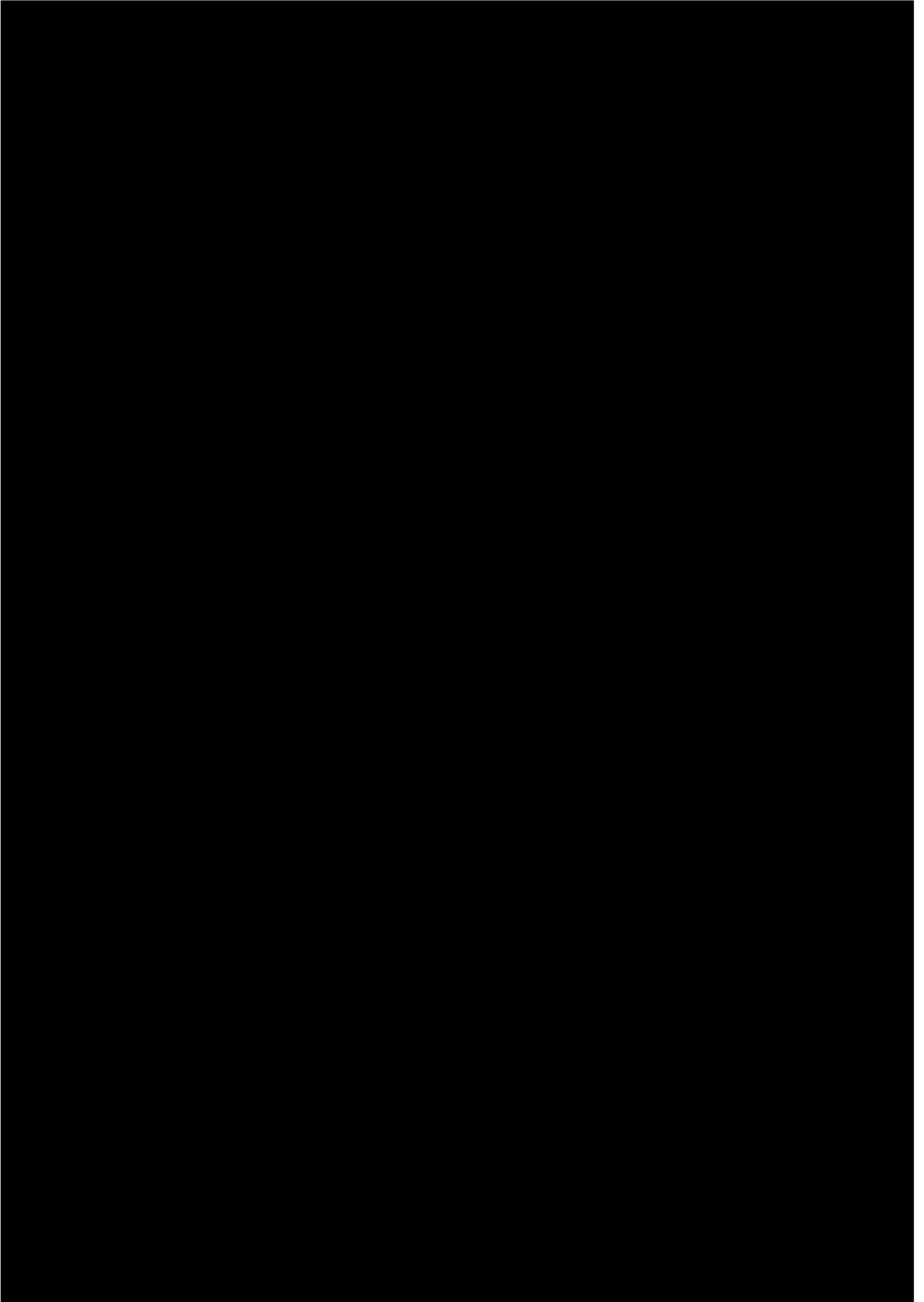


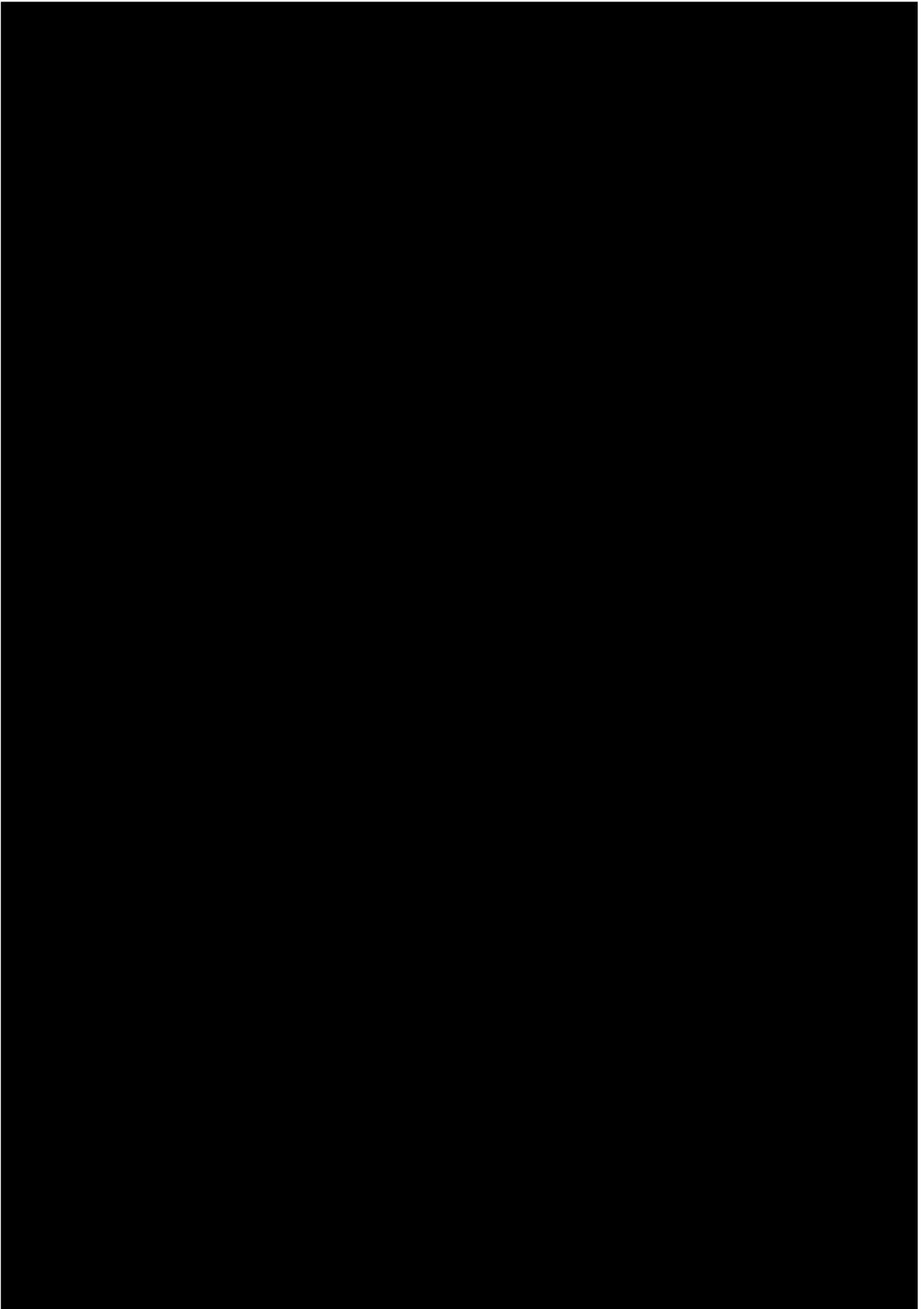


Appendix J: Sealant Injection Raw Test Result Data









Appendix K: Oils OEM RFI

Request For Information - Hydrogen Ready

1. Introduction

This is a request for information relating to oils (including lubricating and hydraulic oils) for Hydrogen service. As part of clean energy initiatives, gas transmission system operators are evaluating the introduction of Hydrogen into their networks, with anticipated staged blending into natural gas systems ranging from approximately 5% up to 100% Hydrogen. Consequently, valves and associated equipment currently operating on natural gas duty within transmission systems may, in future, be required to operate on Hydrogen or Hydrogen/Natural Gas blends as the service medium.

Score Group has been commissioned by a major client to evaluate the impact of Hydrogen on pipeline equipment performance and associated maintenance practices. In this instance, particular focus is placed on the performance and suitability of oils used within the transmission systems, including lubrication of moving components, compressor systems, and any hydraulic functions. Hydrogen service introduces specific challenges such as increased permeation, potential for accelerated degradation, reduced lubricity, and compatibility concerns with elastomers and metallic materials.

Accordingly, a key aspect of this evaluation is the availability, suitability, and proven performance of oils that are compatible with Hydrogen service. This includes both existing products marketed as Hydrogen-ready, as well as any oils that have undergone testing or qualification for use in Hydrogen or Hydrogen-blended environments. This Request for Information (RFI) aims to assess the current market offering of Hydrogen-compatible oils, including any supporting validation, testing data, or development work demonstrating performance under relevant service conditions.

It would therefore be greatly appreciated if you could respond to the following questions where possible. Your input will support our evaluation and inform the selection and recommendation of suitable oil products and manufacturers for future consideration and deployment in Hydrogen service applications.

2. Manufacturer Details

Manufacturer	Business address	Technical Contact	Phone No.	Email

3. General

Below we have a set of initial questions / queries that we are asking to try and help us with the evaluation. Where you believe questions are not relevant, or information is not available, please leave blank.

Q 3.1 Have any operators or users enquired about hydrogen specific oil grades to date?
i.e. have you seen a commercial interest in hydrogen ready oils?

Answer:

Q 3.2 What oils do you currently supply that you consider suitable for hydrogen service, if any?

Answer:

Q 3.3 Would the pressure limits of your current sealant & lubrication compounds change on hydrogen service?

Answer:

Q 3.4 Would the temperature limits of your oils change on hydrogen service?

Answer:

Q3.5 If you have developed any hydrogen ready oils, have they been developed as a brand new product, or are they an extension/modified version of a current product

Answer:

4. Testing

The below questions focus on any hydrogen specific testing carried out on the sealant & lubrication compound range, where applicable.

- Q 4.1 Do you have a test facility/test rig you would typically test your oil products in to prove their effectiveness?
-if so, which parameters/acceptance criteria do you look at during testing to approve a product?

Data Classification: RESTRICTED

Answer:

- Q 4.2 What pressure/temperature would you typically test your oil products to?
- Would pressure/temperature cycles be conducted?

Answer:

- Q 4.3 What fluid would you typically test your sealant and lubrication compounds with? i.e. air / methane / hydrogen

Answer:

- Q 4.4 Have any of your oil products been tested with hydrogen gas?
- if so, was this a hydrogen blend or 100% hydrogen?

Answer:

Appendix L: Greases OEM RFI

Request For Information - Hydrogen Ready

1. Introduction

This is a request for information relating to sealant/lubricants for Hydrogen service. As part of clean energy initiatives, gas transmission system operators are looking at the potential of introducing Hydrogen gas into their networks, with this likely being blended with natural gas in stages, from a 5% mix up to 100% Hydrogen. Therefore valves that are currently operating on natural gas duty within the transmission system, may in future be required to operate on Hydrogen (or Hydrogen / Natural Gas blend) as the service medium.

Score Group have been commissioned by one of our major clients to evaluate the effect hydrogen may have on pipeline valves, and in this particular instance, the effect hydrogen may have on their maintenance techniques; sealant injection as a leakage mitigation strategy and greasing compounds as a lubrication strategy. Therefore, one of the key options in this evaluation is the availability and readiness of sealant injection and greasing compounds which are compatible with hydrogen. This RFI aims to help assess the current offering of Hydrogen ready sealant/greasing compounds in the marketplace as well as any testing / development that may have been carried out to prove performance in this particular service media.

Therefore it would be greatly appreciated if you could answer the below questions where possible, as this will help our evaluation and allow the proposal of sealant compounds and manufacturers for future consideration and use in Hydrogen service.

2. Manufacturer Details

Manufacturer	Business address	Technical Contact	Phone No.	Email

3. General

Below we have a set of initial questions / queries that we are asking to try and help us with the evaluation. Where you believe questions are not relevant, or information is not available, please leave blank.

Q 3.1 Have any valve OEMs or clients enquired about hydrogen specific sealant & lubrication compounds to date?
i.e. have you seen a commercial interest in hydrogen ready compounds?

Answer:

Q 3.2 What sealant & lubrication compounds do you currently supply that you consider suitable for hydrogen service, if any?

Answer:

Q 3.3 Would the pressure limits of your current sealant & lubrication compounds change on hydrogen service?

Answer:

Q 3.4 Would the temperature limits of your sealant & lubrication compounds change on hydrogen service?

Answer:

Q 3.5 If you have developed any hydrogen ready sealant & lubrication compounds, have they been developed as a brand new compound, or are they an extension/modified version of a current compound?

Answer:

4. Testing

The below questions focus on any Hydrogen specific testing carried out on the sealant & lubrication compound range, where applicable.

Q 4.1 Do you have a test facility/test rig you would typically test your sealant and lubrication compounds in to prove their effectiveness?
-If so, which parameters/acceptance criteria do you look at during testing to approve a compound? (i.e. leakage rate, friction reduction etc.)
- Would these parameters/acceptance criteria change depending on a static or dynamic sealing arrangement?

Answer:

Data Classification: RESTRICTED

Q 4.2	What pressure/temperature would you typically test your sealant and lubrication compounds to? - Would pressure/temperature cycles be conducted?
Answer:	
Q 4.3	What fluid would you typically test your sealant and lubrication compounds with?
Answer:	
Q 4.4	Have any of your sealant and lubrication compounds been tested with hydrogen gas? - If so, was this a hydrogen blend or 100% hydrogen?
Answer:	
Q 4.5	If testing has been carried out as per Q 4.4, was it 3rd party witnessed? Please provide copies of any test schedules/results where possible.
Answer:	

S. Design The below questions are focused upon the specific design conditions of the sealant & lubrication.	
Q 5.1	Would the effectiveness of your sealant & lubrication compounds against hydrogen gas depend on any design parameters? - I.e. valve size, component (stem or seat), injection facility design, materials etc.?
Answer:	
Q 5.2	Is there a known limit to the sealing arrangement housing condition in which your sealant compounds can effectively stop leakage? - I.e. is there a maximum pit depth/score depths/surface roughness in which a seat to ball or a stem to bonnet interface can be suitably sealed by your compounds?
Answer:	
Q 5.3	Would there be any specialised equipment/design parameters required to accompany your hydrogen ready compounds to obtain maximum effectiveness?
Answer:	

Data Classification: RESTRICTED

[REDACTED]

