Doctoral Dissertation

Study on autocatalytic decomposition of dimethyl sulfoxide and safe handling system thereof

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Preface

Outlook

Objectives of this study are to elucidate the decomposition mechanism of dimethyl sulfoxide (DMSO) and to establish a safe handling system thereof. On one hand, DMSO is an aprotic polar solvent commonly used in chemical industries. While on the other hand, DMSO is an energetic substance involving a decomposition risk which can lead to an undesired explosion, unless otherwise proper control is taken.

This dissertation consists of six chapters made up of two parts: 1) the elucidation of autocatalytic decomposition of DMSO and 2) the safe handling system of DMSO.

In Chapter 1, "Introduction," the background to this research is described.

In Chapter 2, "What is DMSO?", fundamental aspects of DMSO such as the general synthesis method, physical and chemical properties and characteristics, and DMSO's applications that make use of its unique characteristics are described.

In Chapter 3, "Decomposition of DMSO," risk issues such as the thermal decomposition of DMSO, incompatible substances, autocatalytic decomposition characteristics, and incidents associated with use of DMSO, are described.

In Chapter 4, "Investigations of the mechanisms which rules autocatalytic decomposition of DMSO," various attempts and the results of examining the mechanisms ruling autocatalytic decomposition of DMSO are described.

The first discovery was that several kinds of acids were found in the nonvolatile fraction after complete DMSO decomposition in an inert atmosphere. The addition of a small volume of such acids before starting isothermal heating significantly shortened the induction period. This means that the acids generate *in-situ* meet the general definition of autocatalyst.

Through the analyses of decomposed products, many traces of radical decomposition were observed, suggesting that the main decomposition undergoes *via* radical path.

Through the analysis of turbidity formed during the induction period, methylthiomethanol was found among the intermediates in the liquid phase. It corresponds to a product of Pummerer Rearrangement of DMSO, and it is supposed to be an important intermediate to form methanethiol and formaldehyde.

Behavior of formic acid was examined by various methods, and it was found that formic acid associates with DMSO to create equimolar adduct. The suppression of formic acid vapor is assumed to be due to the association. It was also found DMSO decomposition pathways are influenced by the small addition of formic acid. Through the kinetic study, it was found that the autocatalyst in DMSO decomposition works not in accelerating the main decomposition, but in shortening the induction period.

In Chapter 5, "Safe handling system of DMSO," conditions for autocatalytic decomposition of DMSO are summarized based on the knowledge. Use of DMSO in refining process was discussed to prevent undesired runaway decomposition. The importance of process safety in the chemical industry was reviewed and emphasized. And it is proposed to incorporate safety issue from the early stage of process development in industries.

According to this dissertation, the mechanism of DMSO autocatalytic decomposition is elucidated and useful examples of the application of advanced analytical techniques are introduced to the field of material safety. In addition, safe handling system in DMSO recovery process was proposed based on a series of experimental results and findings.

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Nomenclature

Chemicals

DMSO	Dimethyl Sulfoxide
DMS	Dimethyl Sulfide
DMF	N, N-dimethylformamide
DMAc	Dimethl Acetamide
NMP	N-methylpyrrolidone
ECH	Epichlorohydrin
PAN	Poly(acrylonitrile)
DDW	Distilled Deionized water
FA	Formic Acid
DMDS	Dimethyl Disulfide
BMM	Bis(methylthio)methane
MSM	Methylsulfonyl Methane or Dimethyl Sulfone
TMS	Tetramethyl Silane

Analytical methods and instruments

ARC	Accelerating Rate Calorimetry
DSC	Differential Scanning Calorimetry
IC	Ion Chromatography
TOF-MS	Time-of-Flight Mass Spectrometry
TIC	Total Ion Chromatogram
GC-MS	Gas Chromatography- Mass Spectroscopy

XPS	X-ray Photoelectron Spectroscopy
Ar-GCIB	Argon gas cluster ion beam
PLOT	Porous Layer Open Tubular
LC	Liquid Chromatography
ESI	Electro Spray Ionization
NMR	Nuclear Magnetic Resonance Spectroscopy
DOSY	Diffusion-Ordered Spectroscopy

Others

CCPS	The Center for Chemical Process Safety
AIChE	American Institute of Chemical Engineers
NSC	The National Safety Council, USA
FTA	Fault tree Analysis

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1. Introduction

Primary objective to carry out this Ph. D work was from the author's necessity to propose safety countermeasures and procedures to improve the facilities' handling and usage of DMSO. Many prior studies have discussed the risks in the handling of DMSO, however critical reasons to explain why undesired or unexpected reaction occur have not been clearly identified.

Secondary objective is to address the background of the increased usage of DMSO in the past two decades. Figure 1 illustrates the number of published articles and patents including words "dimethyl sulfoxide or DMSO" according to J-Global database.[1] DMSO was first synthesized by Alexander Zaytsev, in 1867.[2] It is assumed that very little interest was taken in DMSO until the 1940s when chemists started investigating its solvent properties. DMSO was commercially introduced by Crown Zellerbach, the predecessor of current major manufacturer Gaylord Chemical's, in 1962.[3] Shortly after the start of its industrial usage production DMSO received much attention from chemists and engineers due to its excellent solvent properties.[4,5] Such a trend of the times corresponds to its first usage peak around 1970. After the start of the century, the number of publications referencing DMSO have been increasing constantly, suggesting that the application of DMSO has been increasing in various fields. This increasing interest in the usage of DMSO gave rise to the secondary motivations for this study.

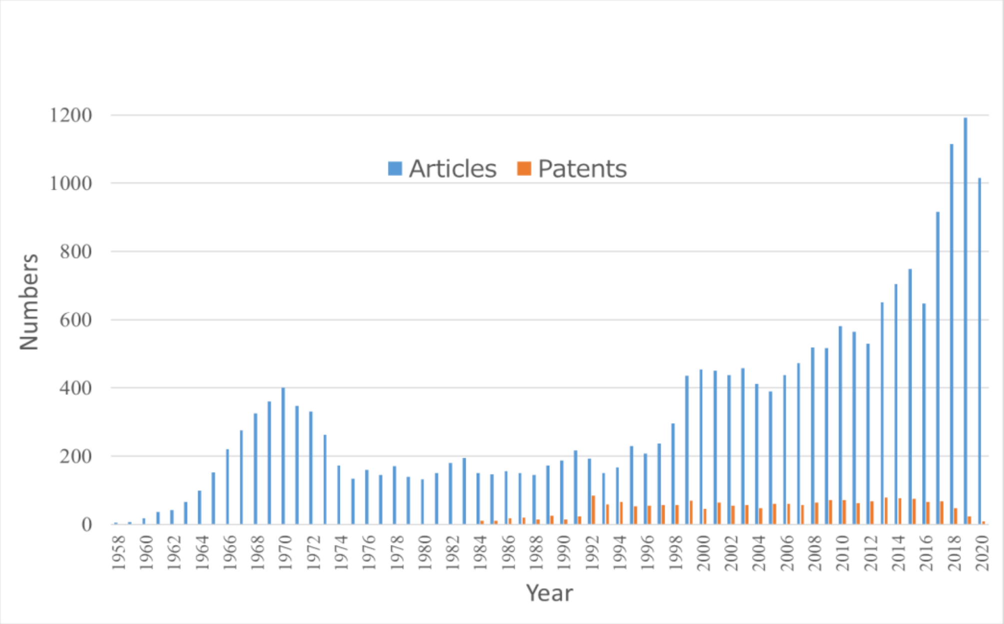


Figure 1. Number of Articles and patents relating to DMSO.

2. What is DMSO?

2.1 Synthesis of DMSO

DMSO is made by the oxidation of Dimethyl Sulfide (DMS) industrially. DMS was produced as a by-product of the pulping process in the paper industries, but it is currently produced by the ethioetherification of hydrogen sulfide and methanol.

2.2 Properties and characteristics of DMSO

Structural formula and three-dimensional structure of DMSO are comparable to acetone as shown in Figure 2. DMSO has various unique properties unlike other solvents, [3-6] and it is widely used as an excellent solvent or as a chemical reagent in the lab work as well as in industries. Typical properties of DMSO are collected by the manufacturer[3] as shown in Table 1.

Table 1. Typical DMSO Properties. (in Alphabetical order)

Parameter	**Value**
Auto ignition temp, in air	300-302 °C
Boiling point (1 atmosphere)	189 °C
Coefficient of expansion	0.00088/°C
Conductivity (Electrical), @ 20°C	3x10-8 (ohm-1 cm-l)
@ 80 °C	7x10-8 (ohm-1 cm-1)
Critical heat flux	4.10x105 J / s / m2
Critical molar volume	2.38x10-4 m3
Critical Pressure	56.3 atm. abs.
Critical temperature	447 °C
Density, at 25 °C	1.0955 g / cm3
Dielectric constant, 1 MHz, @ 20 °C	48.9
@ 40 °C	45.5
Diffusion coefficient	9.0x104 cm2 / sec.
Dipole moment, D	4.3

Evaporation rate index @ 25 °C	
Relative to n-butyl acetate	0.026
Relative to diethyl ether	0.0005
Flammability limits in air	
lower (100 °C)	3 - 3.5% by volume
upper	42 - 63% by volume
Flash point (open cup)	95 °C
Flash point (closed cup)	89 °C
Freezing point	18.55 °C
Heat capacity, ideal gas, Cp(TK)	6.94+5.6x10-2T -0.227x10-4T2
Heat capacity (liq.), 25 °C	0.47 caw g/ °C
Heat of combustion	6054 cal / g
Heat of fusion	41.3 cal/g
Heat of solution in water at 25 °C	-54 cal/g
Heat of vaporization at 70 °C	11.3 kcaVmol
Henry's constant @ 21 °C	991000
Molar freezing point constant	4.07 °C / mol
Molar volume	71.2 cm3 / g
Molecular weight	78.13

Parameter	**Value**
pKa	35.1
pK BH-	-2.7
Refractive index ND@25 °C	1.4768
Solubility parameters	
Hansen's	
- Dispersion	9.0 (cal / cm3)1/2
- Polar	8.0 (ca 1/ cm3)1/2
Hydrogen bonding	5.0 (cal / cm3)l/2
Hildebrand's	13.0 (cal / cm3)112
Specific heat at 29.5°C	0.47 ± 0.015 cal /g rc
Surface tension at 20°C	43.53 dynes / cm
Vapor pressure at 25°C	0.600 mm Hg
Viscosity, cP, at 25°C	2.0
Log octanol-water partition coefficient	-1.35

2.3 Features of DMSO

Most of chemical/physical properties of DMSO are assumed to be from its polar functional group sulfoxide (>S=O). A double bond is customarily placed between the S atom and O atom, but quantum chemistry tells us that the true bonding is a single bond with a polarization giving negative charge on O atom and positive charge on S atom vice versa.[7]

DMSO has pyramidal geometry with a perfect Cs molecular symmetry. The Sulfur atom on the triangular top has a lone pair, providing an ability to work as a ligand to coordinate with cations including protons. DMSO can easily create hydrogen bonds with protic solvents such as water and alcohols. DMSO has a larger dissolving ability than N, N-dimethylformamide (DMF) towards most chemicals.

The DMSO molecule has a large dipole moment, and it was found that liquid DMSO was associated with electron donation from the O atom to the S atom in another molecule. Crystal structure of DMSO was studied at 5 °C by Thomas et al.[8]

The liquid structure of DMSO by X-ray diffraction was investigated by Itoh and Ohtaki[9] followed by Betagnolli et al.[10] Both studies suggested that there was some molecular arrangement of DMSO in the liquid state which was similar to that in the solid state. Molecular dynamics simulation of DMSO was performed by Adya et al.[11] Infra-red spectroscopic studies have been carried out by many authors.[12-16] Solvent induced frequency shifts in the infrared spectrum of DMSO and deuterated DMSO were studied in a wide variety of organic solvents.[17]

Wolfe and Schlegel,[18] Clark et al.[19] and Typke[20] proposed dimer structures for DMSO individually based on quantum chemistry, although the three research groups proposed different dimer structures. It seems logical that some ordered structure exists in liquid DMSO, even if the precise structure is still controversial.

Schematically, the substitution of central carbon in acetone with sulfur gives DMSO. These two chemicals resemble each other in some areas, however, DMSO has much more extensive versatility as a chemical compound than acetone. It is assumed that the S atom in the center of the molecule plays a key role in its unique properties.[21]

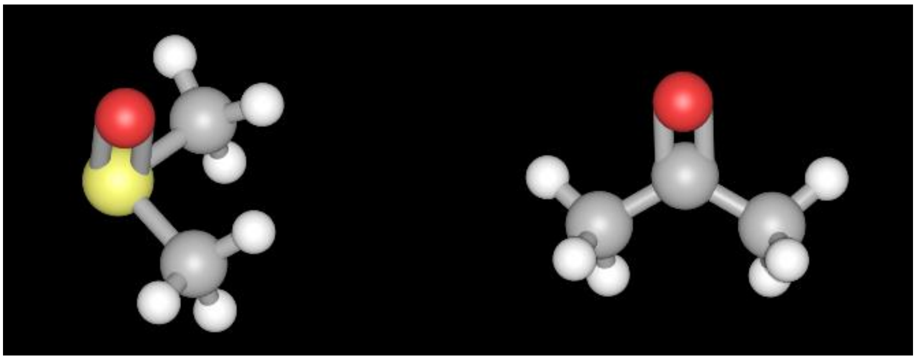


Figure 2. Structural comparison of DMSO (left) and acetone (right).

2.4 Applications of DMSO by making the use of its unique properties.

DMSO is completely miscible with both water and numerous other organic solvents. One exception is saturated hydrocarbons showing very low affinity. DMSO may be used as an extractant of aromatics such as benzene, toluene and xylenes from aliphatic hydrocarbons.[3]

One of its advantages as a solvent is due to its relatively large liquid range (19–189 °C). The second advantage is due to its low biological toxicity described hereafter. DMSO has been primarily developed, and used as a solvent taking advantage of its high dissolving ability.

2.4.1 Use as a reaction medium.

DMSO has been commonly used as a reaction medium due to its excellent dissolving ability, despite it not being an inert solvent.[22] The negative charge on oxygen atoms provides a strong coordination with cations including protons, in contrast to very little coordination with anions. DMSO works as a base to accept a proton, which enables the possibility of adduct formations with strong acids.[23] Determination of pKa or acidities of substrate were performed in DMSO taking into account its leveling effect.[24,25]

To utilize these solvation characteristics, DMSO is used in various chemical reactions in place of other polar solvents such as alcohols by use of these solvation characteristics. Especially, DMSO gives good results as a reaction medium when basic catalyst is used. It is generally required to remove DMSO from the reaction product after use.

2.4.2 Use as an industrial solvent.

The use of DMSO as an “inert” solvent in mechanistic investigations of heterolytic reactions were discussed by Buncel and Wilson.[26] DMSO is actually used broadly across a number of household and industrial cleaning applications from paint stripping to chemical reactor cleaning.[3]

The low biological toxicity, in addition to the high dissolving abilities of DMSO allows it to replace problematic solvents against health and environment such as DMF, dimethyl acetamide (DMAc) and methylene chloride.

PAN fiber with high acrylonitrile (AN) content is produced by wet-spinning method. PAN fiber, as a precursor of carbon fiber, is required to have high uniformity and surface flatness. DMSO is preferably used in such cases as a spinning solvent. After spinning, the contaminated DMSO/water mixture remains at weights that can be several times heavier than the fiber, therefore making it is necessary to recycle such mixtures due to economic and environmental reasons.

2.4.3 High boiling point and low vapor pressure.

DMSO has a relatively high boiling point at 189 °C, and low vapor pressure at ambient temperatures. This makes it convenient in preventing unwilling ignition as well as keeping the environment and atmosphere clean.

2.4.4 Miscibility with water.

DMSO and water can be freely mixed with a generation of hydration heat, due to the formation of the hydrogen bond. The dynamics of the DMSO/water solution with a wide range of water concentrations were studied by Wong et al using ultrafast IR[27]. Polarized model of DMSO and its extension of DMSO/water mixture was proposed by Bachmann[28] to reproduce values such as the molecular dipole moment, the density, heat of vaporization of liquid DMSO.

High miscibility towards both polymeric material and water is beneficial in industrial purposes. For example, unhardened resin is washed out by DMSO, and remaining DMSO on the board shall be removed by water wash in print circuit board production,

2.4.5 Low biological toxicity.

Reported toxicities of DMSO[29] are exceptionally low in comparison to dimethyl formamide (DMF),[30] dimethyl acetamide (DMAc)[31] and N-methylpyrrolidone (NMP),[32] according to OECD Existing Chemicals Database. All these chemicals belong to the same category of “polar aprotic solvents having strong dissolving ability”, though.

To take advantage of its low toxicity DMSO serves as a universal drug carrier in medicinal chemistry and a cryoprotective agent in cell biology. As such, DMSO seems to be the primary solvent used in life science and medical purposes.[33]

However, it should be pointed out when solutions of compounds in DMSO are used, a toxic substance may be introduced in handling.[34]

2.4.6 Use as an oxidant.

DMSO is also used as a mild oxidant in well-known organic redox reactions as exemplified in Kornblum oxidation[35] and Swern oxidation.[36] Inorganic oxidants, such as $KMnO_4$ and $K_2Cr_2O_7$, are so reactive that it may be difficult to control the reaction. Oxidation can take place even at undesired portions of the target substance. Or even unwilling runaway may happen. In contrast to inorganic oxidants, DMSO may be used as a mild site-specific oxidant. In oxidation process, O atom in DMSO is removed to form dimethyl sulfide (DMS). DMS has relatively low bp at 37 °C, and the ease of DMS removal after completion of oxidation may be another advantage of DMSO oxidation.

Many substrates have been subjected for DMSO oxidation, and good yields and selectivity were obtained in many cases.[37-40] It should be noted that Omura et al.[41] stated the reaction of DMSO with trifluoroacetic anhydride could be violent and explosive.1976

2.4.7 Use as a new class of reactant.

In the last two decades, new aspects of DMSO as a useful reagent have been developed to bring various functional groups such as $-CH_3$, -CHO, $-SCH_3$, $-SO_2CH_3$ and -O into the products. Several review papers have been published. [42-44]

2.4.8 New applications in the new era.

DMSO is used as a key substance in new technologies directed towards Sustainable Development Goals (SDGs). In addition to these ongoing developments, several new applications of DMSO in directing sustainable society are under extensive investigation. For example, DMSO was applied for a process of gold recycling with the use of copper bromide for leaching.[45] DMSO was used as a solvent in a hydrogen storage/delivery facility consisting of a CO_2/HCOOH system.[46] DMSO has been investigated as a potential electrolyte for the Li-air battery system.[47] DMSO was utilized as a solvent by combining it with tetraalkylammonium fluoride to dissolve cellulose.[48] A molecular basket sorbents consisting of ethylene glycol derivatives and DMSO was developed and investigated for sulfur dioxide (SO_2) capture from industrial tail gas stream.[49] Present-day, DMSO is an essential substance for creating new technologies including new materials and devices.

3. Decomposition of DMSO

Despite its wide use in both labs and in industries, several serious incidents associated with the use of DMSO have been reported.[50,51] Allan et al. published an alert regarding an intrinsic hazard of using DMSO as a reaction medium.[52] The main reason of incidents is presumably assumed that DMSO was not inert under certain circumstances.

3.1 Thermal decomposition of DMSO

Neat DMSO is stable at temperatures below 150°C, and it begins to decompose slowly near its boiling temperature (189°C).[3,6] However, DMSO decomposes at much lower temperatures in the presence of impurities. Safety concerns have been noted in industrial uses where DMSO is used as a solvent or reactant.[53-65] Since DMSO is recycled daily for economic as well as environmental reasons in industries, many incidents can take place during the recycling process, such as evaporation and distillation.[59] Many researchers have studied the thermal behavior of DMSO and advocated for a safer, more scale-up procedure to using DMSO.

3.2 Incompatible substances for DMSO

DMSO manufacturers have provided lists of incompatible substances. It is actually well-known that DMSO reacts with various chemicals, such as oxidizers[66] including peroxides[67] and peroxides precursors,[68,69] organic and inorganic acids,[70,71] acid halides, acid anhydrides,[72] halogens, halogenated organics, sulfur dioxide[73] and sodium hydride. In the presence of these incompatible chemicals, DMSO decompositions begin at a much lower temperature.[74]

Information on incompatible substances is often nothing but a list, and there is no literature that describes the reaction mechanism of each substance or the relationship between substances. It seems that the following integrated interpretation is possible.

Basic information is that protic acids are known to accelerate DMSO decomposition. Not only do strong inorganic acids catalyze the decomposition, but as do weak organic acids.[75] It is well known that acid derivatives such as acid halides, acid anhydrides and Lewis acids will generate protic acids by hydrolysis. Small amounts of water can be contained even in dry DMSO, as well as water generated during the DMSO decomposition, as described later on. By combining this information, three acid derivatives above shall be treated as same as protic acids with respect to DMSO decomposition.

Similarly, we may describe the function of organic halides which are also well-known incompatibles against DMSO. The reaction of organic halides and DMSO is regarded as the Kornblum reaction, which produces hydrogen halides.[76] The resulting hydrogen halides are the representative DMSO-incompatible substances that cause decomposition.[77] In other words, organic halides are the precursor of hydrogen halides in the presence of DMSO. Therefore, the acceleration effect of organic halides shall be dealt as same as hydrogen halides.

The function of alkali is rather complex. Alkali, of course, weakens the acidity by neutralization. This is probably the reason why the DMSO manufacturers recommend that recovery such as evaporation and distillation be performed under weak alkaline conditions.[6] However, it has been pointed out empirically that high-concentration alkali rather promotes decomposition, and the effect of alkali seems to be intricated.

Øpstad et al. found radical formation from DMSO in the presence of a small amount of a base.[78] Cardillo and Girelli reported that DMSO decomposed in air through a non-autocatalytic but a radical-like mechanism.[2] It is no wonder that DMSO, as an organic material, undergoes oxidative decomposition due to oxygen, and oxidative decomposition is considered to be a radical mechanism. Bases may retard decomposition by neutralizing the acid on one hand, and they may produce radicals on the other hand.

Anyway, it is important for all users to know the fact "DMSO is not an inert solvent, but an effective reaction medium."[79]

3.3 Autocatalytic decomposition of DMSO

The other important aspect observed in DMSO decomposition is its autocatalytic nature. Although the definition of autocatalyst or autocatalytic decomposition may vary by author, the overview described by Stoessel[80] is widely acknowledged: "A reaction is called autocatalytic, when a reaction product acts as a catalyst on the reaction course." Under certain circumstances, it is known that DMSO decomposes autocatalytically with a relatively long induction period and steep exothermic peak, as shown in Figure 3.

Decomposition proceeds slowly in the flat portion called "induction period", and this period lasts for a relatively long time without activity. Rapid exothermic decomposition then eventually exceeds the slow decomposition rate, leading the mixture to undergo a runaway reaction. It is difficult however to predict sudden heat evolution given the unexpected timing of initiation. This is why it is important to understand the behavior of autocatalytic decomposition.[81,82]

Firerz points out the risk of the distillation process even under vacuum, where unstable compounds are treated. Thermal safety assessment was carried out for

DMSO.[83]

Brogli et al.[84] reported that the autocatalytic decomposition of DMSO occurred when aliphatic bromide was mixed with DMSO and that small amounts of zinc oxide extended the induction period and moderated the self-accelerating decomposition process once it occurred. Hall[85] reported seven incidents associated with DMSO decomposition in his paper, and some cases were related to autocatalytic decomposition or lacked an adequate thermal history for the DMSO.

In the early stages of popularizing the process of accelerating rate calorimetry (ARC), Cardillo and Girelli[2] carried out DMSO decomposition experiments using ARC both in nitrogen atmosphere and in the air. In their results, the ARC self-heating curve of DMSO in nitrogen atmosphere showed a long induction period, whereas DMSO thermolysis in the air showed no such induction period. The researchers realized that some acids were formed when decomposition was carried out in the air; notably, they mentioned that DMSO decomposed in the air through a non-autocatalytic radical-like mechanism, although the detailed mechanism was not discussed. Several others have studied DMSO decomposition to address industrial concerns, but there was no consensus with respect to the chemical structure and function of autocatalyst.

Prolonged storage of DMSO at elevated temperature, or storage conditions of contaminated DMSO even at room temperature may cause the accumulation of decomposed substances, which catalyze further decomposition when heated again.[80] As a result of inconspicuous decomposition, it may be too late to return to normal conditions by the time one notices an abnormality in temperature and/or pressure. DMSO handling risks in industrial settings may arise from this characteristic decomposition profile.[85]

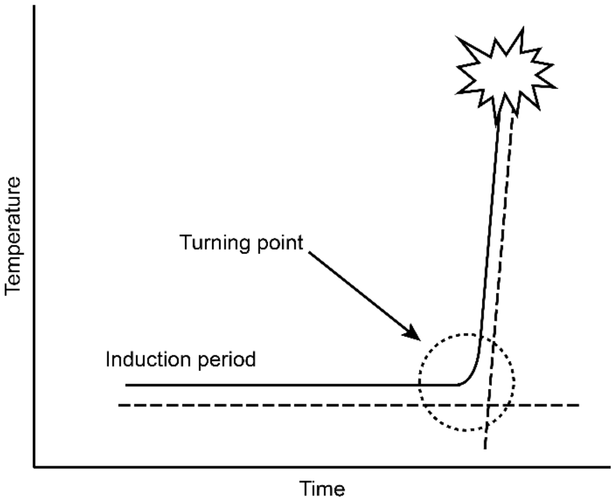


Figure 3. Schematic diagram of autocatalytic decomposition.

3.4 Incidents associated with the use of DMSO.

Industrial incidents associated with the use of DMSO are reported by Hall collectively.[59] In addition, Bretherick's handbook[51] and databases are available on global websites, such as the National Institute of Advanced Industrial Science and Technology, Japan (AIST)[87], and the Ministry of Health, Labor and Welfare, Japan[88].

In some sense, it seems logical that there are no incidents documented when handling DMSO only. Neat DMSO is stable enough at temperatures below 150 °C. In most cases however DMSO contained foreign materials or contaminants, and the undesired reactions were likely to have happened when crude samples of DMSO were heated.

Since it is difficult to obtain a detailed investigation report for each incident, we need to rely on secondary information. For example, an explosion that took place in a plant where sugar ester was manufactured, specifically during the DMSO evaporation phase and the details of the accident and the results of the investigation have been reported by the company itself.[89] The cause of the incident was analyzed and Investigators concluded as follows;

- There was an extremely high number of accidents involving DMSO as a single solvent causing explosion and fire due to abnormal exothermic reactions during the recovery distillation phase.
- DMSO causes explosive decomposition that is not considered normal decomposition.
- Remarkable exothermic showed at 250 °C or higher than that according to the evaluation by DSC.
- Exothermic peak started at around 220 ° C, but when 5% hydrochloric acid was added thereto, exotherm started from 110 ° C according to ARC.
- When same amount of NaOH was added to DMSO, exothermic peak started at 200 ° C, which means it was more dangerous than neat DMSO.
- When DMSO is used as a synthetic solvent for pharmaceuticals and pesticides, bromine compounds are often contained or DMSO distillation is often carried out under acidic conditions. This may drive the on-set temperature level to shift down to lower temperatures.
- When ECH or sucrose is contained, inner temperature of the distillation tower rises due to their heat of polymerization and decomposition, which is thought to induce the decomposition of DMSO.
- In conclusion, thermal recovery of DMSO requires the strict control of contaminants and heat source temperatures.

Epichlorohydrin (ECH) is a fundamental raw material for epoxy resins, and the ECH/DMSO mixture is another example where exception detail investigations have been carried out by government research institutes.[90,91] Several important findings were outlined based on the investigations.

- The thermal hazard of a mixture of ECH with DMSO is higher than either ECH or DMSO.
- The exothermic onset-temperature for a mixture of ECH with DMSO does not depend much on the content of ECH in the mixture.
- The first exothermic peak in the DSC curve of a mixture of ECH with DMSO is mainly attributed to the formation of mono- and di- chlorohydrins.
- The second exothermic peak in the DSC curve of a mixture of ECH with DMSO is mainly attributed to the decomposition of mono- and di- chlorohydrin formed from the reaction corresponding to the first exothermic peak.

The severity of incidents caused by the foreign materials varies widely and depends on the incompatibility of foreign materials. The most severe incident documented was an explosion caused by mixing perchloric acid with DMSO.[50] A bromoamine titrator using perchloric acid was set-up in a laboratory. The titrator of the perchloric acid container appeared to be empty, so the technician mistakenly plugged in the DMSO container Immediately upon connection, the DMSO container exploded, and the technician died in the subsequent fire. This was an exceptional incident as perchloric acid is highly reactive against DMSO, even at room temperature, and the mixing of these two chemicals should be strictly prohibited. Although it is necessary to educate workers in the laboratory and take strict measures to prevent erroneous operation, it is out of the scope of this study because it is assumed not to happen in industries.

One of the synthetic uses of DMSO is to obtain sodium methylsulfinylmethide (known as dimsyl sodium) and use it as a methylating agent. Dimsyl sodium is synthesized from a paraffin suspension of DMSO and NaH at around 70 ° C. Many incidents have occurred, from lab scale experiments to plant scale mass production, in preparation of dimsyl sodium.[92-94] According to brief incident reports, it was documented that the mixtures exploded, and the ejecta. There is always the risk of thermal reactions with Dimsyl anion, however such undesired reactions takes place not at room temperature, but at around 70 ° C. Since the dimsyl sodium is prepared for the purpose of methylation, the risk / benefit balance should be carefully considered. The use of DMSO may be unavoidable in fine chemistry such as pharmaceutical manufacturing, and thus thorough risk assessment should be carried out to take sufficient measures in the same way as dimsyl sodium. This is the reality of DMSO, but such high-risk applications are not included in the scope of this study.

$$CH_3S(=O)CH_3 \quad + \quad NaH \quad \rightarrow \quad CH_3S(=O)CH_2^{-}\cdot Na^{+} \quad + \quad H_2\uparrow \qquad (1)$$

The mildest reactivity among incompatibles is observed for organic halides except for epichlorohydrin. Hard to dissolve solutes that require strong dissolving ability of DMSO often contain organic halides, and such contaminated DMSO is recycled in industries using medium pressure steam (0.4MPaA, 144 ° C). This stability category is the central scope of this study.

3.5 Supercritical fluid

Generally, materials include three phases such as solids, liquids, and gases. Phase change is linked to the combination of temperature and pressure. For example, water changes from ice to liquid water and further to water vapor depending on the temperatures and pressures. The state under temperature and pressures above the critical point is called supercritical fluid. Gases and liquids are indistinguishable above this critical point.

It is known supercritical water has extremely high oxidizing power, even high-quality metals resistant to corrosion are corroded by supercritical water. Another example of this behavior is; carbon dioxide in a supercritical state, dissolves various substances well. Supercritical carbon dioxide is used in the process such as decaffeinating coffee, extraction of odorous components of garlic, and active ingredients of functional foods.

In the process of DMSO decomposition in a closed vessel, DMSO is placed in a high temperature and high-pressure environment. It is possible that the contents can reach a supercritical state. According to Nikitin,[95] the critical temperature is reported to be 718 ± 7 K from the experimental measurement , and 720-729 K from various other calculations.

4. Investigations of the mechanism which rules autocatalytic decomposition of DMSO.

4.1 Exploratory research of autocatalyst

Many thermal investigations have been carried out, though very little attention has been paid to the nature of autocatalyst compared to the tracking of thermal behaviors. We are unsure the reason why autocatalysis have not been characterized, although the incompatibles that enhance the decomposition of DMSO are well known, If a catalytic substance is present in the volatile fraction, it will be found and characterized by GC-MS analysis. No extensive analysis has been carried out for non-volatile fractions. It was supposed that the catalytic substance was present not in the volatile fractions but in the non-volatile fractions. The first investigation began with the analyses of non-volatile fractions.

4.2 Reagents and gases

DMSO (99.98%) was purchased from Fujifilm Wako Pure Chemical Corporation, Japan.

Other chemicals used for analysis were reagent grade, and water was deionized and distilled in the laboratory. The analytical gases used were highly purified and designated for GC−MS analysis.

4.3 Thermal treatment of DMSO and the analysis of the nonvolatile fraction.

4.3.1 Experimental Section

4.3.1.1 Analytical instruments for qualitative analysis.

Differential scanning calorimeters (DSC) were as utilized to carry out the thermal treatment of DMSO. A small portion (*ca.* 2 mg) of DMSO was poured into a high-pressure pan for DSC made of stainless steel, which was sealed using a dedicated press machine. All sample preparations were carried out in a nitrogen glove box.

Thermal treatment was performed using a DSC 7000X from Hitachi High-Technologies Japan under a constant heating rate of 10 °C/min from room temperature to 430 °C. Completion of DMSO decomposition was verified by the absence of an exothermic peak in a second run.

After cooling, the stainless-steel pan was mechanically opened under liquid nitrogen, and the inner wall of the pan was washed with distilled deionized water (DDW). The resulting extract was examined by ion chromatography (IC) in an instrument equipped with an electroconductivity detector and mass detector. The ion chromatograph was a Thermo Scientific DX-600 equipped with an electroconductivity detector. For TOFMS, an Agilent LC/MSD TOF was used. The columns used were Thermo Scientific IonPac AG11-HC and AS11-HC. Experiments were conducted in ESI-negative mode.

4.3.1.2 Isothermal heating test and analysis of the resulting material.

The isothermal heating test was carried out using accelerating rate calorimeter (ARC), and the detailed experimental conditions are as follows. For ARC, a TIAX accelerating rate calorimeter was used, conducted in a nitrogen atmosphere at temperatures of 160, 170, and 185 °C. The sample bomb was an SUS316. The sample amount was 3.5 g. The minimum sensitivity was 0.02 K/min. The cutoff temperature was 200 °C. The test period was 10000 min maximum.

Samples were isothermally heated in the bomb at 185 °C for 2000, 4000, and 6000 min, and were analyzed to determine acid concentration. The isothermal heating test was repeated from the beginning every time since intermediate sampling from the closed vessel was difficult.

After cooling, the resulting solution was diluted 10 times with DDW and subjected to IC analysis. For IC, a Thermo Scientific Integrion RFIC was used, with an electroconductivity detector and columns of IonPac AG18-4 μm + AS18-4 μm (4 mm φ × 150 mm). The eluent was the KOH gradient with the use of an eluent generator.

4.3.1.3 Effect of acid addition on DMSO decomposition.

A small portion of acid was added to the DMSO before the start of the isothermal heating test using ARC. The concentrations of the representative acids were taken from the data point at 6000 min and 185 °C. In the acid investigation, the headspace was filled with helium, and the temperature was set to 185 °C.

To determine the effect of the environmental gas, air and carbon dioxide were individually introduced into the DMSO. A small tube was used as a bubbler, and the headspace of the ARC bomb was carefully sealed with the same gas.

An isothermal heating test was also conducted on these samples at 185 °C. Detailed ARC experimental conditions are as follows: For ARC, a THT Euro ARC was used, under a helium atmosphere for acid investigation and at a temperature of 185 °C. The sample bomb was an SUS316. The sample amount was 3.0 g. The minimum sensitivity was 0.02 K/min. The cutoff setting was 400 °C or 12.0 MPa. The test period was 250 h maximum.

4.3.2 Results and Discussions

4.3.2.1 Analysis of the nonvolatile fraction after DMSO decomposition.

Ion chromatograms of the nonvolatile fraction after complete decomposition are shown in Figure 4. Sulfuric acid (H_2SO_4) and methanesulfonic acid were identified by their retention times. Two peaks with relatively short retention times were analyzed by time-of-flight mass spectrometry (TOFMS), as shown in Figure 5, and the identification data are summarized in Table 2.

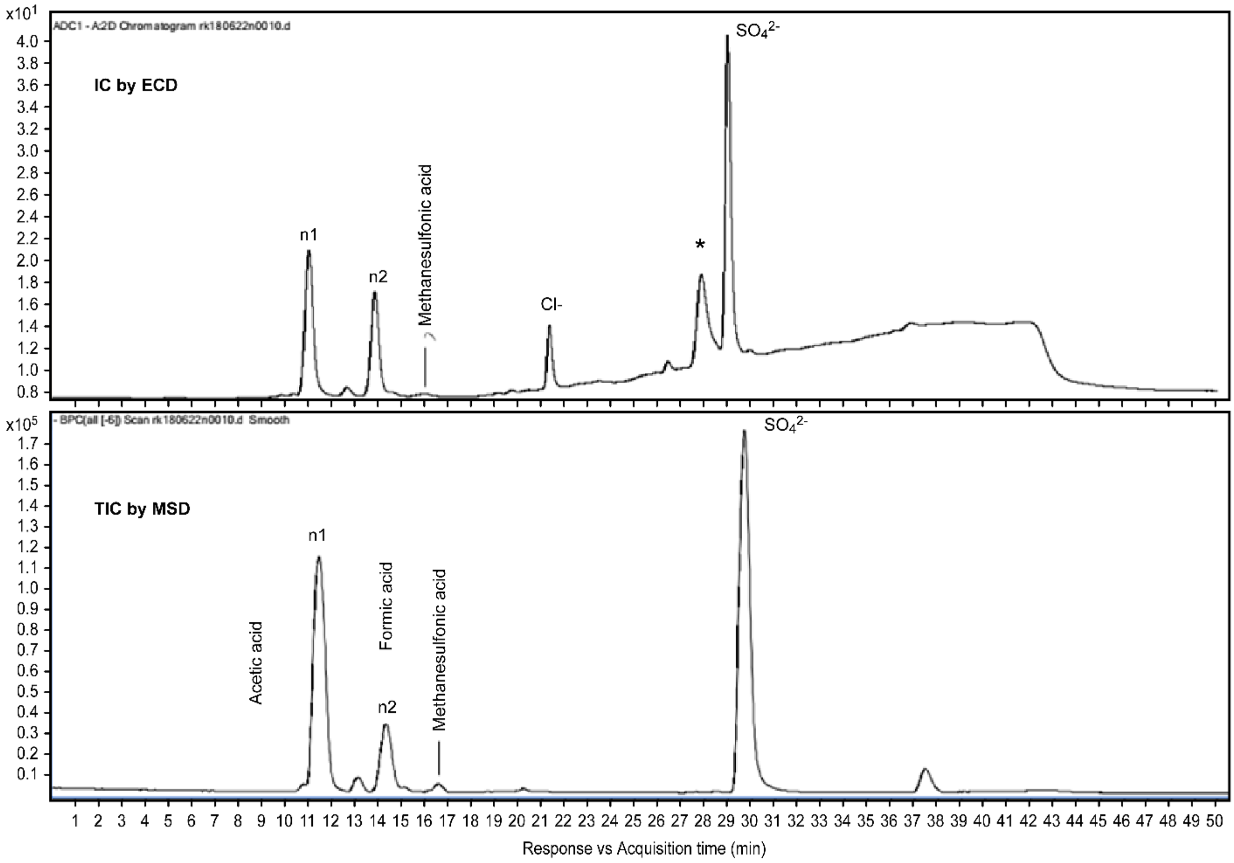


Figure 4. Ion chromatograms obtained for the nonvolatile fraction. Upper: data recorded by the electroconductivity detector, lower: total ion chromatogram (TIC) recorded by the mass detector.

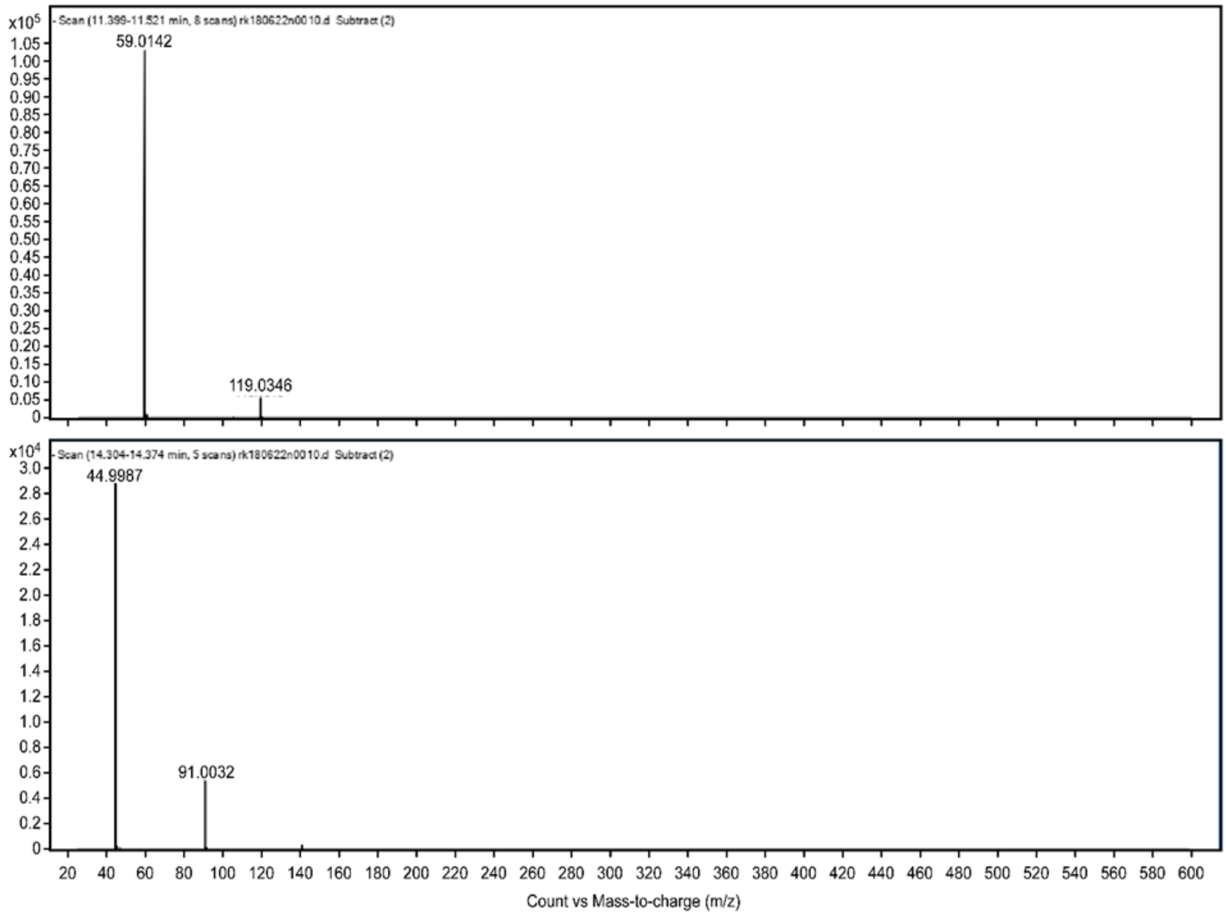


Figure 5. TOFMS data obtained for the carboxylic acids. Upper: Peak #1, lower: Peak #2.

Table 2. Identification data of carboxylic acids

Peak number	m/z, detected	Estimated Ion	Estimated Composition	Calculated Mass	Matching Ratio (%)*1	Estimated Compound
n1	59.0142	$[M-H]^-$	$C_2H_4O_2$	60.0211	86.04	Acetic Acid
n2	44.9987	$[M-H]^-$	CH_2O_2	46.0055	97.52	Formic Acid

Note*1: Matching ratio was calculated from the combination of three factors (1) Difference between detected m/z and calculated one, (2) Difference between detected isotope ratio and calculated one, and (3) Mass difference between detected isotope and calculated one.

Sulfuric acid (H_2SO_4) was considered to be the oxidized product of sulfurous acid (H_2SO_3), while H_2SO_3 itself was not detected. Formation of sulfur dioxide was reported by Thyrion and Debecker,[57] and water formation was found by Traynelis and Hergenrother[55] in the analysis of the volatile fraction after DMSO decomposition

Santosusso and Swern[56] observed the *in-situ* generation of the strong acids, methanesulfonic acid and sulfuric acid, when DMSO was heated with peroxide. The same authors[58] claimed that they carried out qualitative analysis of the acids by using an ion-exchange isolation technique, but unfortunately, no detailed information regarding the analysis was provided. The creation of these strong acids was confirmed in our experiment.

It has been reported that peroxide or air is necessary to generate sulfuric acid from DMSO; however, nothing other than DMSO existed in this experiment. It is noted that sulfuric acid and methanesulfonic acid can be generated without peroxide in an inert atmosphere.

A simple question arises with respect to the identity of the oxidizer in this inert atmosphere. Named organic reactions such as Kornblum oxidation[35] and Swern oxidation,[36] both of which utilize DMSO as a selective oxidizer, suggests that DMSO can be an oxidizer as well as a reactant in an inert atmosphere at elevated temperature. Similarly, acetic acid and formic acid were thought to be the oxidized products of the corresponding aldehydes.

Many authors have analyzed the volatile fraction in DMSO decomposition; however, the non-volatile fraction seems to have been a blind spot in prior studies.

4.3.2.2 Isothermal heating tests and analysis.

Isothermal heating tests were carried out for neat DMSO at three temperatures, and no exothermic peak appeared at 160 and 170 °C within the standard testing time of 10,000 min. When the isothermal heating test was performed at 185 °C, a steep exothermic peak appeared at approximately 9000 min, as shown in Figure 6.

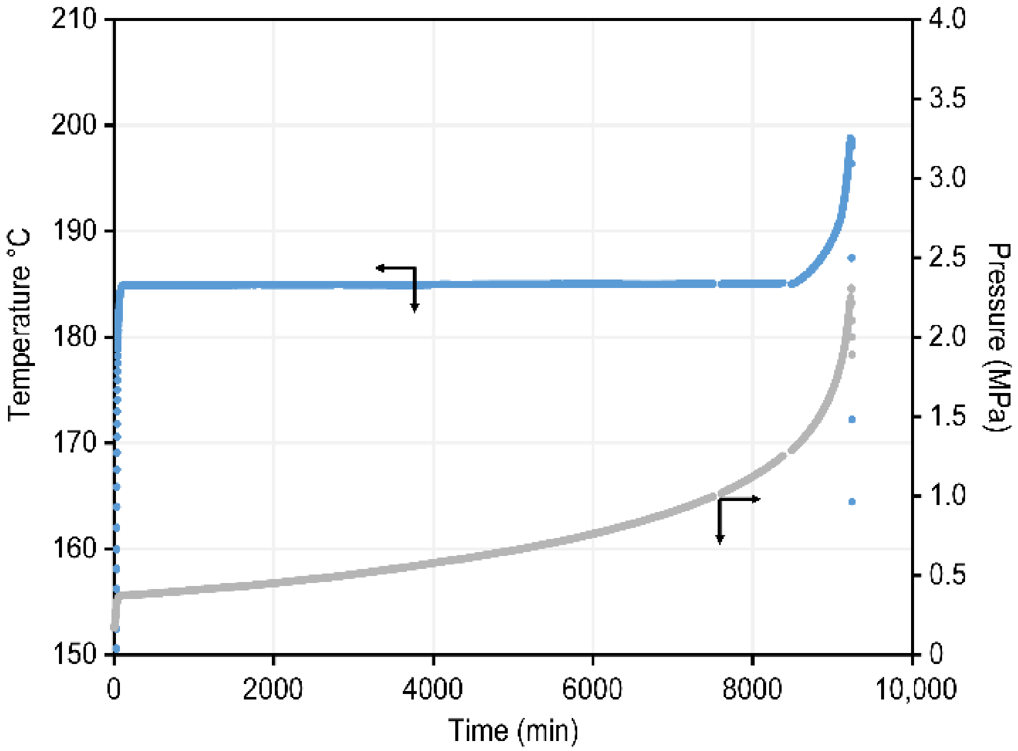


Figure 6. Isothermal heating test (1): Temperature and pressure time course obtained for DMSO.

It is worthwhile to note that DMSO actually underwent exothermic decomposition near but and below its boiling temperature in a closed system, without any foreign impurities. This thermal behavior was regarded to be a characteristic of autocatalytic decomposition with a long induction period. The acid concentrations in the intermediate samples are summarized in Table 3.

Table 3. Acid concentrations in the intermediate samples heated at 185°C

Time elapsed (min)	*Acid Concentration (mg/L)*					
	Lactic acid	Acetic acid	Methane-sulfinic acid	Formic acid	Methane-sulfonic acid	Sulfuric acid
2,000	＜10	＜10	＜10	67	9.8	＜8
4,000	＜10	＜10	14	220	24	8.4
6,000	21	＜10	23	2,100	130	38

Several kinds of acids were found in the MS analysis, and the number of acidic species detected here were greater than that detected in the DSC experiment above. It was assumed that the reason for this was that the isothermal heating sample by ARC was carried out at 185 °C, much lower than the final temperature of ramp DSC test, and the intermediate sample was collected in the early point of the induction period where most part of DMSO remained unreacted. Because of their thermal stability, limited acids were supposed to remain after the complete decomposition of DMSO.

The concentrations of acids rose during the heating phase, suggesting that acids were generated and gradually accumulated in the inert atmosphere during the induction period. Formic acid showed the highest concentration followed by methanesulfonic acid and sulfuric acid. These acids were generated and accumulated during the induction period, and they are assumed to act as catalysts in the decomposition of DMSO.

4.3.2.3 Accelerating effects of acids in the isothermal heating test

The effect of formic acid was compared to that of blank DMSO, as shown in Figure 7. The sample containing 2000 ppm formic acid exhibited a steep exothermic peak shortly after 50 h, while the blank DMSO exhibited a peak shortly after 200 h. Thus, the acceleration effect of formic acid became obvious, approximately 1/4 of the way through the induction period.

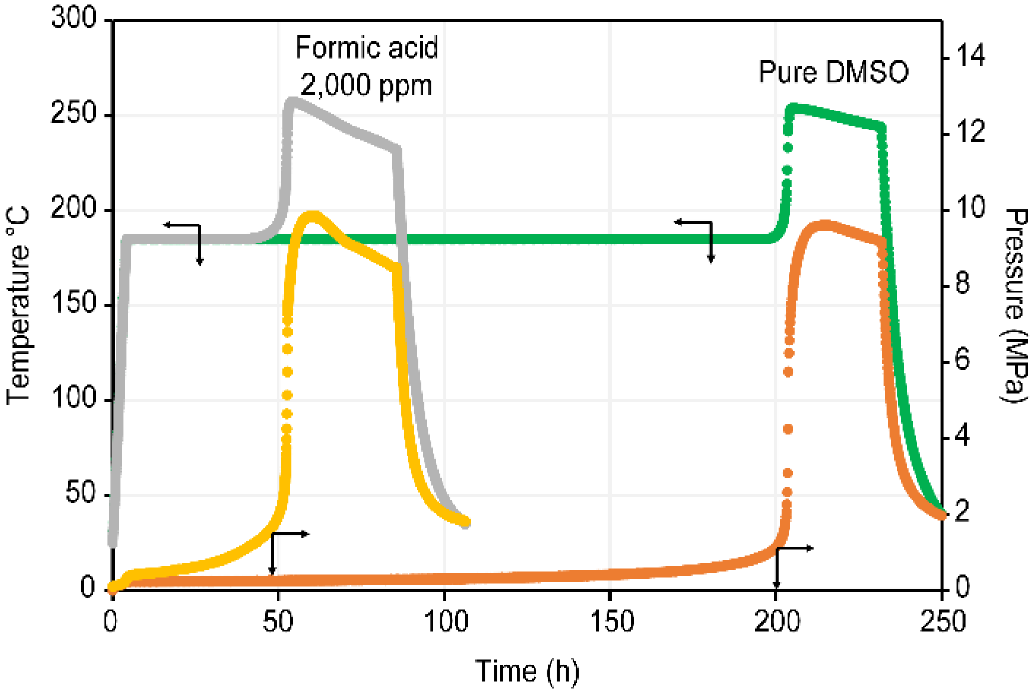


Figure 7. Isothermal heating test of DMSO: Effect of formic acid.

Similarly, 130 ppm methanesulfonic acid and 40 ppm sulfuric acid were compared to blank DMSO, as shown in Figure 8. Both acids exhibited an acceleration effect, and the steep exothermic peak of the sample containing 130 ppm methanesulfonic acid began much earlier than that of the sample containing 40 ppm sulfuric acid. Considering the strength of these acids in water, sulfuric acid (pKa −3.19 ± 0.15)[96] is many orders of magnitude stronger than methanesulfonic acid (pKa 1.75 ± 0.50),30 but methanesulfonic acid unexpectedly showed a larger acceleration effect on DMSO decomposition. Similarly, although formic acid is a weak acid with a pKa of 3.74 ± 0.10,30 the sample containing 2000 ppm formic acid showed the largest acceleration effect on the induction period among the acids investigated.

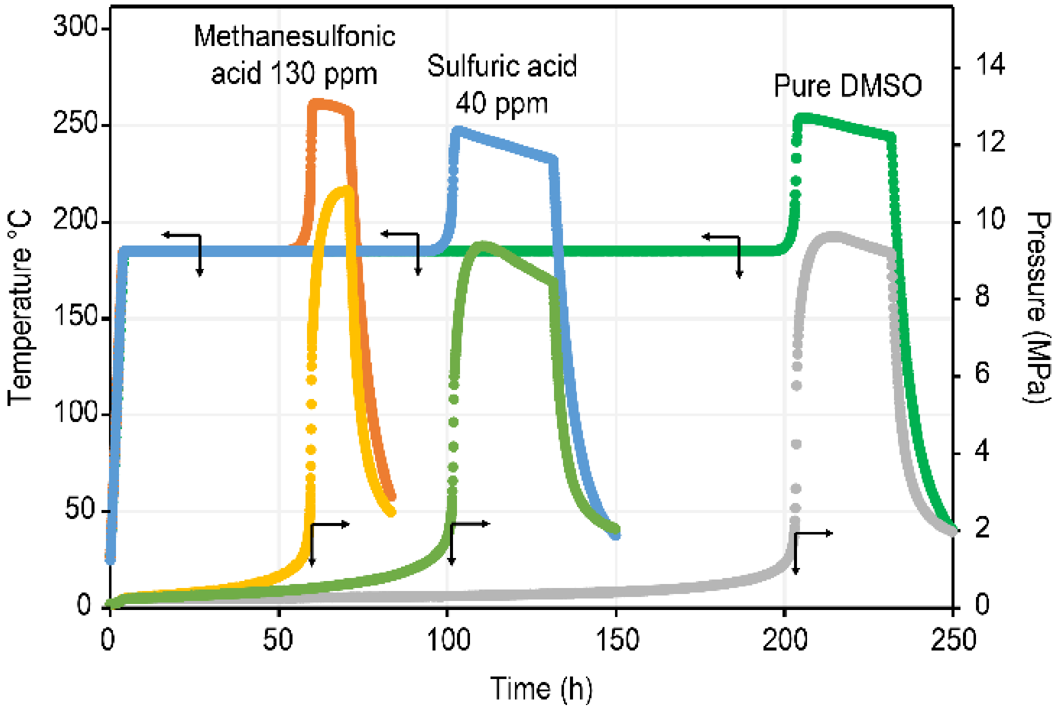


Figure 8. Isothermal heating test of DMSO: Effects of methanesulfonic acid and sulfuric acid.

The effects of the environmental gases were notable, as shown in Figure 9. Bubbling coupled with the filling of air in the headspace of the ARC bomb showed the largest acceleration effect in this study, confirming Cardillo and Girelli's results[2].Oxygen in the air was believed to play an important role in acid generation, as described by Santosusso and Swern.[56,58]

Regarding the effect of carbon dioxide, two explanations may be possible: (1) Carbonic acid (H_2CO_3) was formed in the ARC bomb due to the addition of carbon dioxide with existing water and acted as an acid or (2) CO_2/DMSO worked effectively in the reaction as this combination has recently been found to significantly advance DMSO oxidation.[97]

It is known that carbon dioxide can be a convenient supercritical fluid to extract valuable substance, since it is non-toxic, easily available, easily removable, and it has a moderate critical temperature. An idea to use binary mixtures of CO_2 and DMSO may be possible in terms of extraction efficiency.[98] Regardless, it is suggested that the combination of CO_2/DMSO should be avoided when DMSO is recycled.

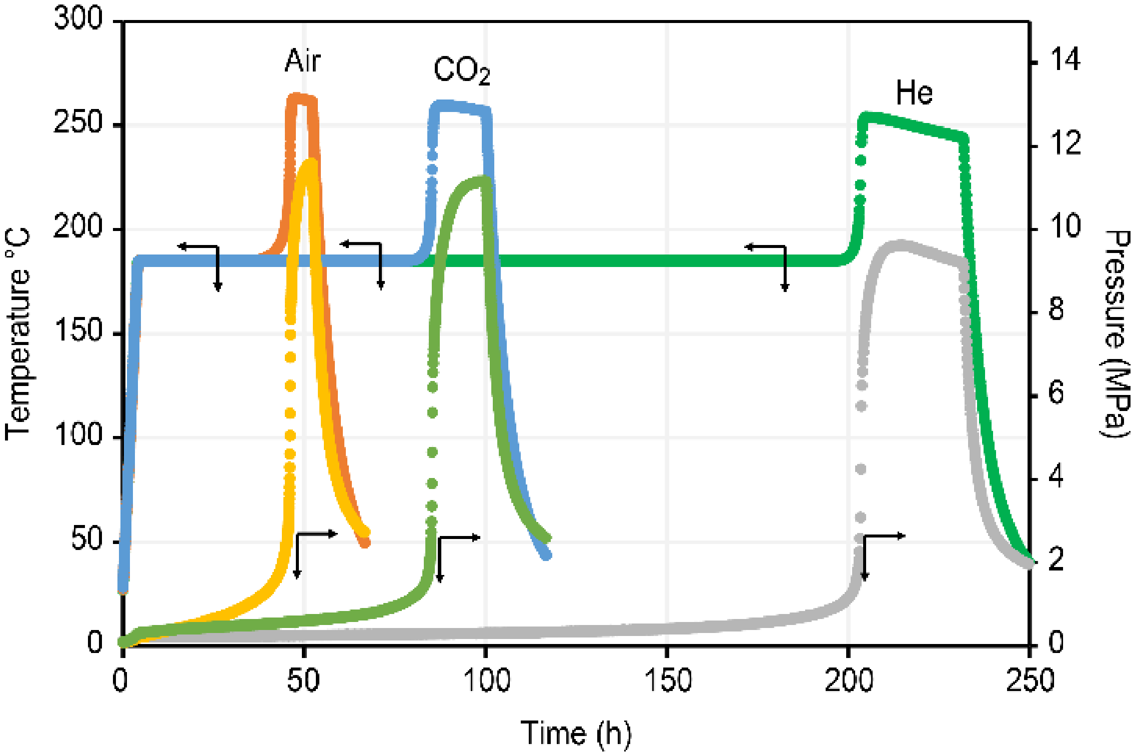


Figure 9. Isothermal heating test of DMSO: Effect of environmental gas.

4.3.3 Brief conclusions of this section

Several acids were found in the non-volatile phase after DMSO decomposition, even when the thermal treatment was carried out in an inert atmosphere. It was also found such acids accumulated over heating time, and small addition of such acids shortened the induction period of DMSO decomposition. The acids generated *in-situ* seems to meet Stoessel's definition of an autocatalyst.

It is common knowledge among the scientists concerning the safe handling of DMSO that acids highly accelerate the decomposition of DMSO, so it can be said that the inventive step of this dissertation study lies in the recognition that acids are generated from neat DMSO at elevated temperatures even in an inert atmosphere.

In this section, the analytical study was combined with isothermal heating tests to elucidate the autocatalysts involved in DMSO decomposition. The relevant findings were as follows:[99]

i. Several kinds of acids were found in the nonvolatile fraction after complete DMSO decomposition in an inert atmosphere.
ii. DMSO itself was believed to act as an oxidizer as well as a reactant in the generation of acids.
iii. DMSO underwent a runaway reaction at 185 °C, which is near but below its boiling point (189 °C), even in an inert atmosphere.
iv. Runaway decomposition of DMSO was accompanied by a long induction period, and no foreign impurities were required to undergo runaway.
v. Several kinds of acids were found in the reaction mixture taken from the intermediate sample in the isothermal heating test, and their concentrations increased over heating-time.

vi. The addition of a small amount of acids before starting isothermal heating significantly shortened the induction period.

vii. 2000 ppm formic acid showed a larger acceleration effect for DMSO decomposition than 130 ppm methanesulfonic acid or 40 ppm sulfuric acid. It was unexpected when considering the pKas and contents of three acids.

viii. The induction period also decreased when air or carbon dioxide was bubbled and filled in the headspace of the ARC bomb.

4.4 Precise analyses of volatile phase and residual moiety on the bottom after DMSO decomposition.

In order to identify the autocatalytic mechanism, it is necessary to not only identify the autocatalysts, but also decomposed substances. Since the results of analyzing the non-volatile fraction that can dissolve in water were already discussed in the previous sections, the other fractions need to be analyzed.

On one hand, the analysis of the volatile phase during or after DMSO decomposition has been investigated by many researchers, and many substances and relating information have been reported. However, there are some safety concerns in sampling from a closed vessel under pressure. We came up with the idea of applying the microcapillary technique, often used for the pyrolysis of polymers aimed for qualitative analysis,[100] to the decomposition study of DMSO.

On the other hand, in the DSC experiment that confirmed the formation of acid, we realized that the bottom of the DSC pan was discolored and some components, that were insoluble in water, remained. An attempt was made to analyze the substances remaining on the bottom of the container after DMSO decomposition.

4.4.1 Experimental Section

4.4.1.1 Procedure for the thermal treatment of DMSO and the analysis of the volatile fraction.

The microcapillary technique was used here to analyze the volatile fraction of DMSO after its thermal decomposition. In a nitrogen glove box, small portion (*ca.* 2 μL) of DMSO was poured into a small glass capillary tube with one end closed. The open end was temporarily sealed with aluminum foil, and soon after removing the capillary from the glove box, the open end was fused with a small gas burner.

The sealed capillary tube was then placed into a pyrolyzer installed on the GC injection port. After undergoing thermal treatment in the pyrolyzer, the capillary tube was crushed by pushing the attached plunger in to allow the material content to go into the GC-MS. Nitrogen gas was then introduced into the pyrolyzer to carry out the decomposition in an inert atmosphere.

4.4.1.2 Investigation of the temperature program: ramp heating vs instant heating.

In the preliminary DSC trials, several temperature levels were chosen for the final temperature with a ramp rate of 10 °C/min. Since all DMSO was consumed when the maximum temperature was set to 430 °C, the furnace temperature of the pyrolyzer was set to 430 °C hereafter to analyze the decomposed products. Two temperature programs (Methods A and B) were designed, and the chromatograms were compared.

Method A: The furnace temperature was raised from 70 °C to 430 °C at a rate of 10 °C/min. The capillary tube was broken when the furnace temperature reached 430 °C. Method A was intended to represent ramp heating.

Method B: The furnace temperature was preliminarily adjusted to 430 °C, and the capillary tube was inserted thereto. According to the tracking test of residual DMSO, the storage time in the furnace was set to 7 minutes to complete DMSO decomposition. Seven minutes after the insertion, the capillary tube was broken using the plunger, as described above. Method B was intended to represent instant heating.

Analytical instruments for GC-MS analysis were as follows. The pyrolyzer was a Frontier Lab Multi Shot Pyrolyzer EGA/PY-3030D. For GC-MS, an Agilent GC-7890A system was combined with JEOL JMS-T100CGv.

4.4.1.3 Thermal decomposition of DMSO using DSC, followed by the surface analysis of the inner wall using XPS.

Even on a small scale, DMSO runaway decomposition is vigorous and somewhat risky. Therefore, a minimum thermal decomposition experiment was carried out using the DSC system as a decomposition chamber. A small portion (*ca.* 2 mg) of DMSO was poured into a high-pressure stainless steel DSC pan, and was sealed using a dedicated press machine. All preparations were carried out in a nitrogen glove box to ensure an inert atmosphere.

Thermal treatment was performed using a DSC 7000X from Hitachi High-Technologies, Japan, under a constant ramp rate of 10 °C/min from room temperature to 430 °C. After thermal treatment, the pan was opened mechanically using a precise diamond cutter equipped with a liquid nitrogen cooler. An opened pan with a dark brownish color at the bottom was washed with DDW thoroughly using an ultrasonic cleaner. After air-drying at room temperature, the pan was subjected to X-ray photoelectron spectroscopy (XPS) analysis.

XPS is a convenient surface-sensitive quantitative technique that can analyze the elemental composition (parts per thousand), empirical formula, chemical state and electronic state of the elements that exist in the specimen.[101] XPS uses an X-ray beam as a probe, which is an advantage of this method, without restricting the type of sample material.

According to the standard procedure in surface analysis, argon gas cluster ion beam (Ar-GCIB) sputtering was applied to clean the top surfaces of the test specimen. A wide spectrum was then taken to obtain an overview of the composition at first, and then a narrow spectrum was taken to focus on the status of the particular element of interest. In this study, the S2p spectrum was recorded for sulfur. The same procedure was repeated as above, except for using a Au-coated pan instead of an ordinary SUS pan.

4.4.2 Results and Discussions

4.4.2.1 Analysis of the volatile fraction after DMSO decomposition.

Many peaks were found and identified in the volatile fraction of DMSO by GC-MS analysis as shown in Figure 10. There was no difference in the peak number between Method A (ramp heating) and Method B (instant heating), which indicates that there is no large difference in the decomposition products as long as the final temperature is set to 430 °C, where no DMSO remains.

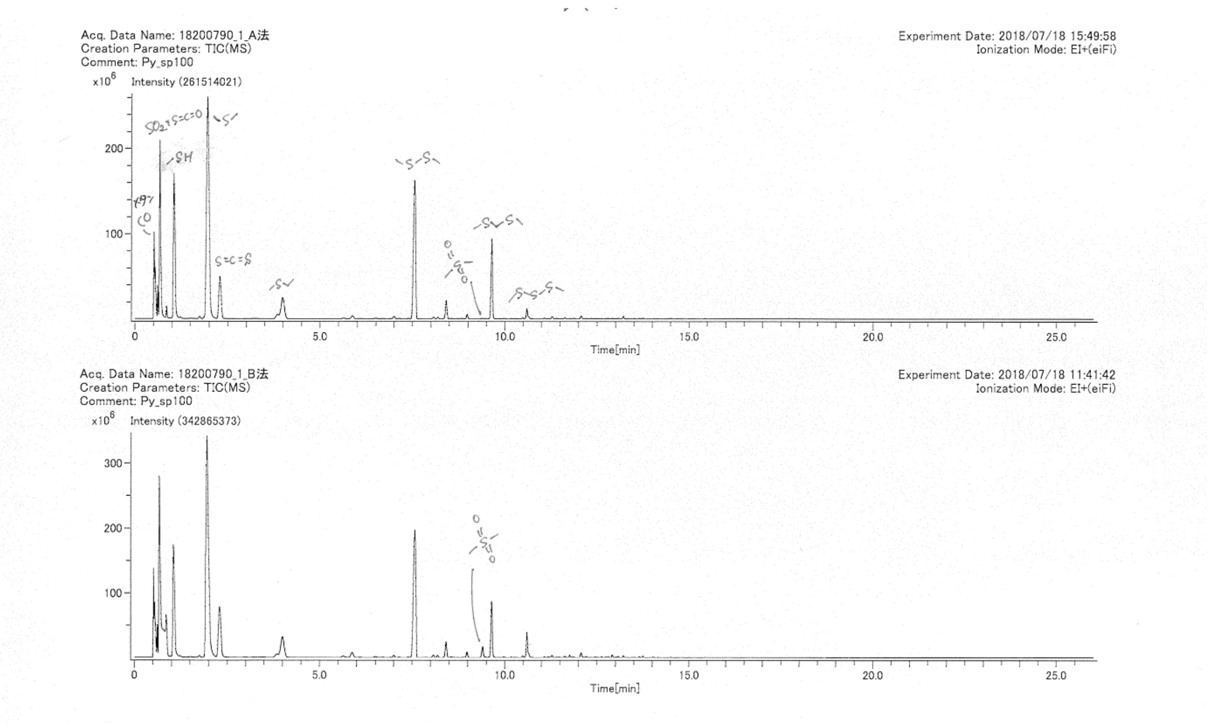


Figure 10. GC-MS Total Ion Chromatogram obtained for neat DMSO decomposed in an inert atmosphere. Upper: Method A and Lower: Method B.

The peak assignment by GC-MS was summarized in Table 4. Various sulfur-containing substances were found in the high boiling point (bp) zone, such as dimethyl sulfide (DMS), dimethyl disulfide (DMDS), bis(methylthio)methane (BMM), carbon disulfide, methylsulfonyl methane (MSM, or dimethyl sulfone), and a series of polysulfides with the general formula CH_3-$(S)_n$-CH_3.

Table 4. Peak Assignment for the Decomposed Substances by GC-MS. High bp Zone

Peak	Assignment	Peak	Assignment	Peak	Assignment
1	Carbon monoxide, Methane, Carbon dioxide and Ethylene	7	Acetone	13	Dimethyl disulfide
2	Hydrogen sulfide	8	Ethanethiol	14	$C_2H_6S_2$
3	Carbon sulfide and Sulfur dioxide	9	Dimethyl sulfide	15	Methyl methanesulfonate
4	Water	10	Carbon disulfide	16	Dimethyl Sulfone
5	Sulfur dioxide	11	Ethyl methyl sulfide	17	Bis(methylthio)methane
6	Methanethiol	12	CH_4S_2	18	Dimethyl trisulfide
				19	$C_8H_{12}S$

HP-1, 0.32 mm ID × 30 m with a 5 µm PDMS layer, was used for the separation column. Method A was used for the thermal program of pyrolyzer. The GC-MS conditions were as follows: The carrier gas was He with a flow rate of 1.0 mL/min. The injection temperature was 300 °C. The temperature program of GC started from 40 °C (5 min hold) to 260 °C (10 min hold) with a ramp rate of 20 °C/min. The split ratio was 1/50. The interface temperature was 260 °C, and the ionization temperature was 250 °C. The monitoring range was m/z 15-800.

Under the first analytical conditions employed, low bp substances were not separated enough. The peak separation was improved by using a porous layer open tubular (PLOT) column that provided good separation for low bp compounds. Many peaks were observed and identified in the low bp zone, as shown in Table 5. Notably, some of the molecules no longer contained sulfur.

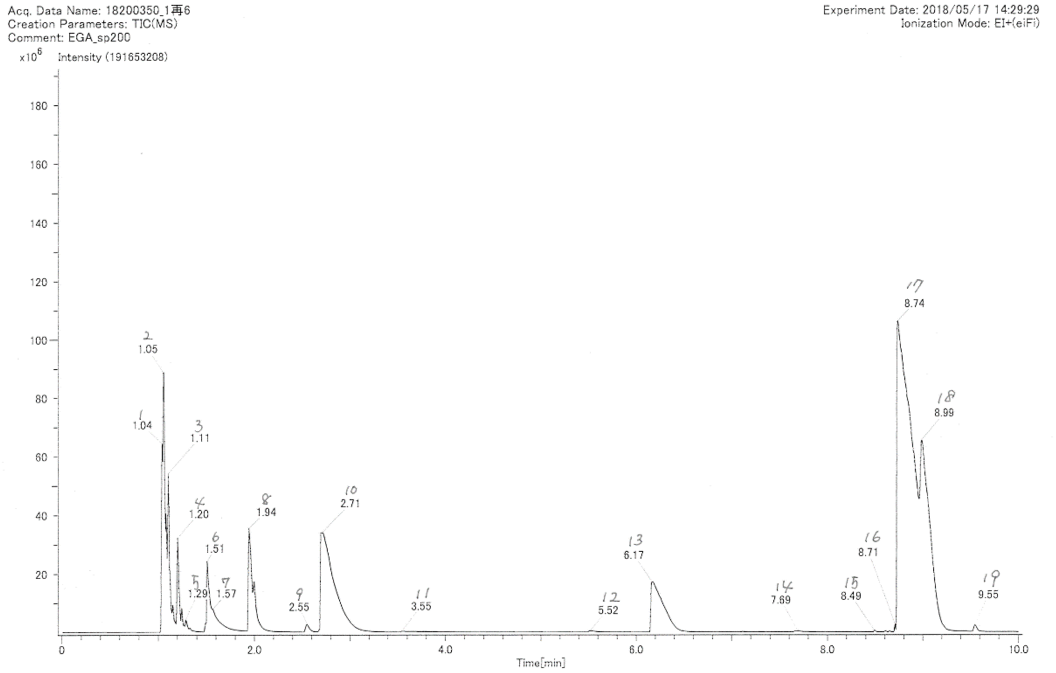


Figure 11. Improved GC-MS total ion chromatogram using a PLOT column.

Table 5. Peak Assignment for the Decomposed Substances by GC-MS. Low bp Zone

Peak	Assignment	Peak	Assignment	Peak	Assignment
1	Carbon monoxide	7	Formaldehyde	13	Methanethiol
2	Methane	8	Carbonyl sulfide	14	Ethanol
3	Carbon dioxide	9	Propene	15	Acrolein
4	Ethylene	10	Sulfur dioxide	16	Ethanethiol
5	Ethane	11	Methanol	17	Dimethyl sulfide
6	Water	12	Acetaldehyde	18	Carbon disulfide
				19	Thiirane

Supel-Q PLOT, 0.32 mm ID x 30 m with a 15 μm porous layer, was used for the separation column. Method A was used for the thermal program of pyrolyzer. The GC-MS conditions were as follows: The carrier gas was He with a flow rate of 1.0 mL/min. Injection temperature was 300 °C. The temperature program of GC started from 40 °C (5 min hold) to 250 °C (10 min hold) with a ramp rate of 20 °C/min. The split ratio was 1/200. The interface temperature was 260 °C, and the ionization temperature was 250 °C. The monitoring range was m/z 15-800.

It was found that carbon dioxide, formic acid and sulfuric acid greatly shortened the induction period of DMSO decomposition.[99] It is ironic, but carbon dioxide as well as the precursors of the acids above, such as formaldehyde and sulfur dioxide, were found in the low bp range.

In addition, we found two monomers which had the potential to be polymerized. One was formaldehyde, and the other was ethylene. Traynelis and Hergenrother[55] demonstrated the formation of formaldehyde during refluxing DMSO for 3 days in the presence of ethylene glycol or acetamide. Thyrion and Debecker[57] carried out DMSO thermolysis at temperatures beyond 300 °C and stopped at 20% conversion, and they found ethylene formation in the gas phase. However, it is uncertain whether these monomers can polymerize to provide exotherms in this system.

When overviewing the analytical results in the volatile fraction, it is apparent that several new chemical bonds, such as C-C, S-S, C=O and S-H, are created during thermal decomposition. It is rational to think that the various new bonds are the result of the concurrent scission and recombination of the original bond. Additionally, it is assumed that only a radical reaction can give such results. Radical paths exist in the process of DMSO decomposition.

These new bonds were observed again in the resulting products obtained at lower pyrolyzer temperatures, such as 300 °C, where DMSO remained. Thus, it can be assumed that radical paths also exist in the relatively early stages of DMSO decomposition.

The other interesting observation was the valence of sulfur atoms; most substances found in the volatile fraction contain divalent S (II). In our previous study, acids, including formic acid, acetic acid, methanesulfonic acid and sulfuric acid, were found in the water extract of the nonvolatile fraction after the decomposition of DMSO.[99] Such acids are oxidized products, and the mass balance of oxygen in oxidation/reduction should be maintained in a closed vessel. As a result, reduced products are likely to come to the volatile fraction, while oxidized products tend to come to the nonvolatile fraction.

One exception, found in the volatile phase, was methylsulfonyl methane (MSM) having S (VI). DMS and MSM are considered disproportionation products, as shown in

Eq. 2; however, the DMS peak seemed to be larger than that of MSM. There may be some alternative pathways rather than disproportionation in the formation of DMS.

2 DMSO → DMS + MSM (2)

Although there is one paper stating that DMS accelerates DMSO decomposition,[77] no such catalytic effect was found in DMS according to Babasaki et al.[75] or our own study. It is assumed that the volatile fraction does not contain the autocatalytic substances.

4.4.2.2 Thermal decomposition using DSC followed by surface analysis using XPS.

Photographs of the mechanically opened pans before XPS analysis are shown in Figure 12. A dark brownish color indicates that something existed on the bottom surface. First, Ar-GCIB sputtering was applied to clean the top surfaces. Some enhancement was observed in the minor peak. However, there was no significant differences in the before and after sputtering, which meant that the observed peaks were not from the surface contaminants, but from adhered substances on the bottom of the pan. It can be assumed that some decomposed materials produced a thin layer on the metal surface.

The XPS narrow spectra obtained that reveal the chemical status of the sulfur for the two kinds of pan are shown in Figures13-16. By referring to Figures 13 and 14, the main peak is found at approximately 164 eV in the case of the Au-coated pan. In addition, a shoulder peak is observed at approximately 162 eV in the case of the SUS pan, as shown in Figures 15 and 16. The peak ratio of the main/shoulder and corresponding energy levels are passably reproducible in these two cases. According to the XPS handbook[101] or NIST database,[102] a peak at 164 eV is assigned to atomic sulfur

S (0) or organic divalent sulfur S (II), whereas a peak at 162 eV is assigned to met al. sulfide.

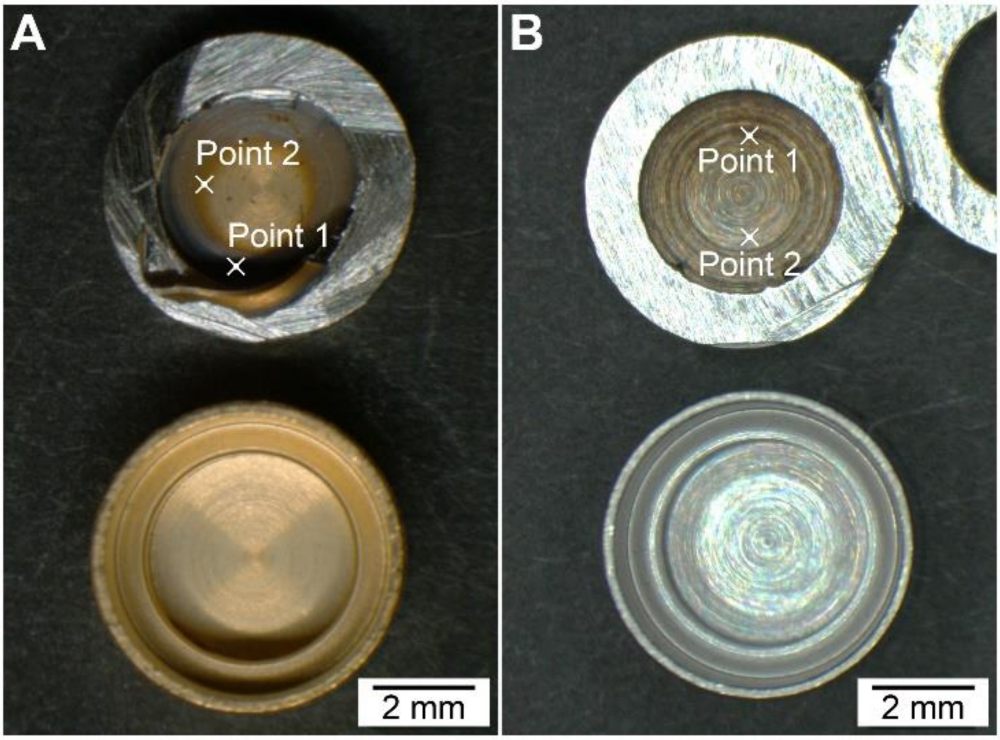


Figure 12. Photo image of the mechanically opened DSC pan.
Left: Au-coated pan Top: After the decomposition of DMSO, Bottom: Blank pan
Right SUS pan Top: After decomposition of DMSO, Bottom: Blank pan
Blank pans without DMSO were thermally treated using the same heating program.

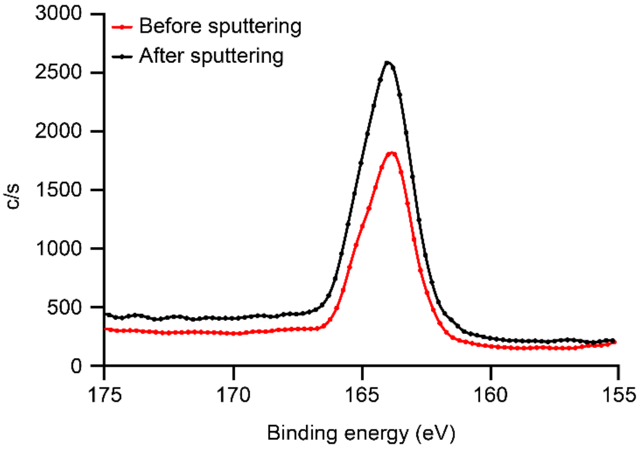


Figure 13. XPS narrow spectrum recorded for the Au-coated pan. Point 1.

Red line is the spectrum taken at point 1 before sputtering

Blue line is the spectrum after sputtering of the same portion.

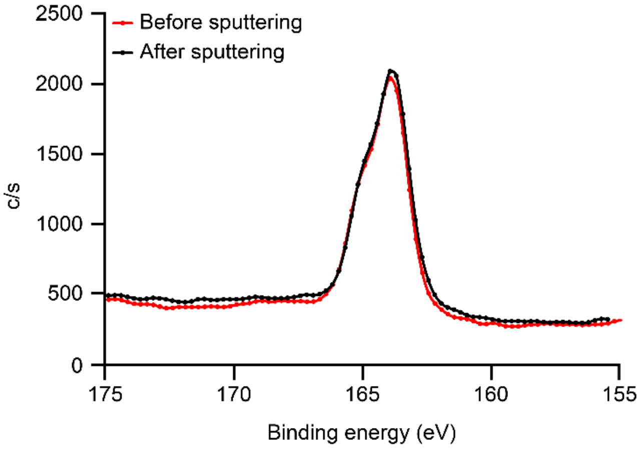


Figure 14. XPS narrow spectrum recorded for the Au-coated pan. Point 2.

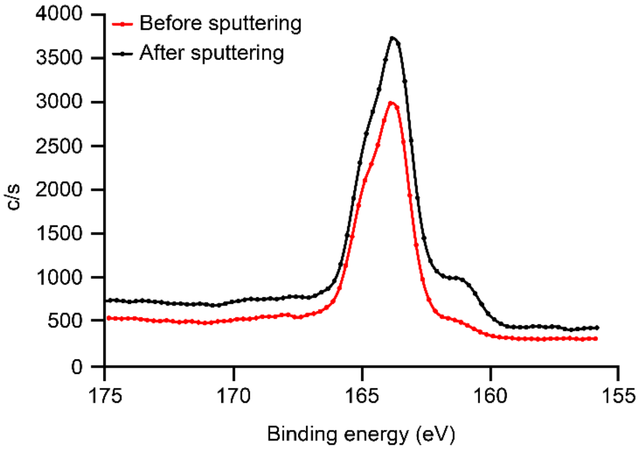


Figure 15. XPS narrow spectrum recorded for the SUS pan. Point 1.

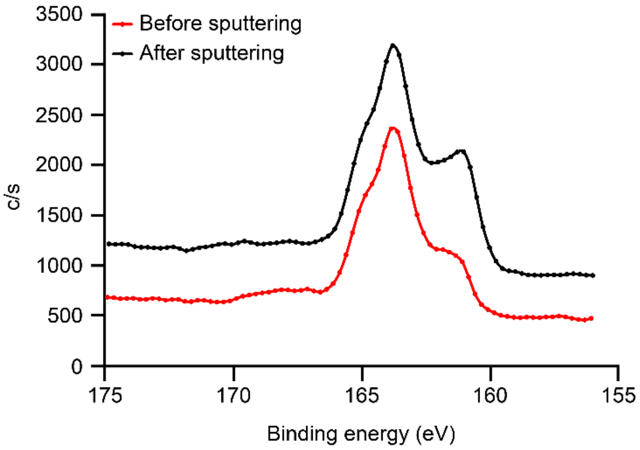


Figure 16. XPS narrow spectrum recorded for the SUS pan. Point 2.

There is a limitation in principle in the XPS determination of whether the thin layer consists of S (0) or organic S (II), as these two statuses present peaks at almost the same XPS bonding energy. However, important information was observed with respect to the shoulder peak at 162 eV. This peak was not observed when a Au-coated pan was used, while the main peak at approximately 164 eV was observed, which was the same as that of the SUS pan. It is known that sulfur reacts with most met al.s at high temperatures to form met al. sulfides, but gold and platinum are the exceptions.[103] The precise oxidation state of sulfur at 164 eV is not clear at this moment; however, it is assumed that a met al. sulfide is generated from the sulfur source in the SUS pan to give a peak at 162 eV. In contrast, it is assumed that there is no chance for a sulfur source to create a met al. sulfide in the Au-coated pan.

Sulfur is a unique element with the largest number of allotropes consisting of cyclic and linear molecules. Notably, the cyclic octamer S_8 is the most stable allotrope among all.[104] This stabilization effect comes from the symmetrical structure of the S_8 ring. As some oligosulfide-type substances were found in the GC-MS analysis above, they may be candidates for the residual substance.

In addition to oligosulfides, dimethyl sulfide (DMS) and bis(methylthiomethane) (BMM), both belonging to a group with the general formula CH_3-(S-CH_2)n-S-CH_3, were found in the GC-MS analysis as described above. Although DMS and BMM. may not have a chance to remain at the bottom due to their relatively low boing points, and a higher molecular weight compound in the same group may be another candidate for the residual material.

Either way, some of the sulfur atoms in DMSO are reduced during decomposition to form a residual substance on the inner wall of the vessel. Sulfuric acid was found after thermal the decomposition of DMSO.[57] Interestingly, the reduction and oxidation of sulfur occur simultaneously in one vessel.

4.4.3 Brief conclusions of this section

In this section, chemical analyses of the decomposed products were performed to elucidate the main decomposition of DMSO. Through our investigations, we propose that the main decomposition of DMSO occurs *via* a radical path. Since acids generated *in-situ* are regarded as autocatalysts, it is supposed that the decomposition promoter is switched from an acid to a radical somewhere at the turning point as shown in Figure 3. No substance thought to have an autocatalytic function was found both in the volatile phase and the residue on the bottom of the DSC pan. The interesting findings are described as follows:

i. In the analysis of the volatile fraction after DMSO decomposition, many substances were found. Among them, carbon dioxide, which is known to shorten the induction period. Formaldehyde and sulfur dioxide are assumed to be converted to formic acid and sulfuric acid, respectively, and both work as autocatalysts.

ii. Several new chemical bonds were found in the decomposed materials through GC-MS analysis, which indicates the presence of radical reactions.

iii. After thermal decomposition using DSC, a dark brown color remained on the inner surface of the pan. When a Au-coated pan was used, a peak was found at approximately 164 eV in the XPS narrow spectrum. This peak is assigned to atomic sulfur S (0) or organic divalent sulfur S (II).

iv. When the SUS pan was used instead, a shoulder peak was observed at approximately 162 eV in addition to the main peak. A peak at 162 eV is assigned to metal sulfide.

v. Some sulfur atoms in DMSO seem to be reduced during decomposition to form residual substances on the inner wall of the vessel.

4.5 Intermediate substances formed in the induction period.

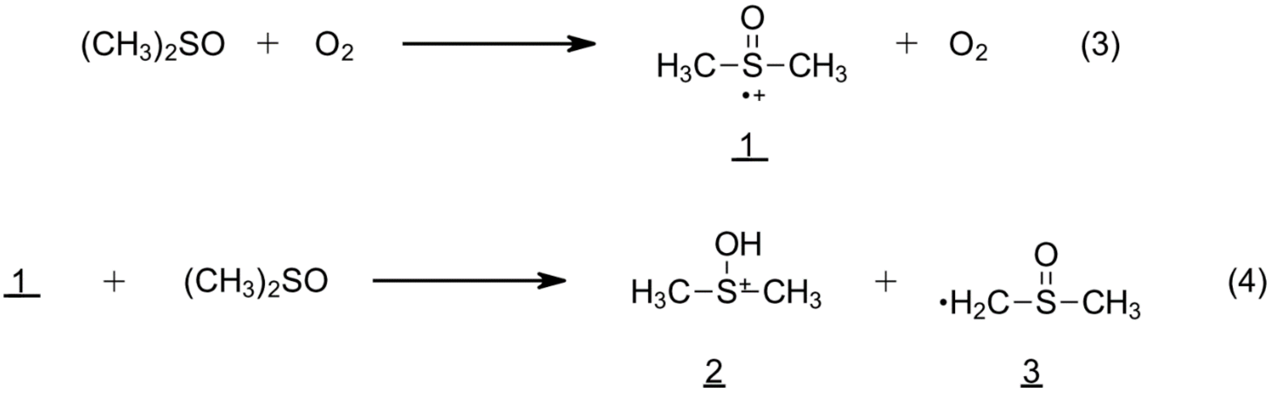
It seems to be quite reasonable to analyze the intermediate sample during the decomposition as well as final sample to understand the complicated process. Many prior studies carried out such analyses.

Nace and Monagle[105] probably first reported the formation of low-boiling point products such as dimethyl sulfide (DMS), methyl mercaptan (MM) and dimethyl disulfide (DMDS) when DMSO was reacted with organic halides. They described that a large amount of formaldehyde was formed when an acid acceptor was not utilized to remove the acid produced in the reaction.

Traynelis and Hergenrother[55] refluxed DMSO for 3 days to obtain 3.7% decomposition products consisting of paraformaldehyde, DMS, DMDS, bis (methylthio)methane BMM and water.

Head and McCarty[54] heated DMSO in a Curius tube at 180 °C for 68 hours in the presence or absence of oxygen. When the atmosphere was completely replaced by nitrogen gas, no decomposition took place during thermal treatment. In contrast, they confirmed the complete decomposition of DMSO in the presence of oxygen; observing phase separation in the resulting solution as well as a white solid deposited around the reaction vessel seal.

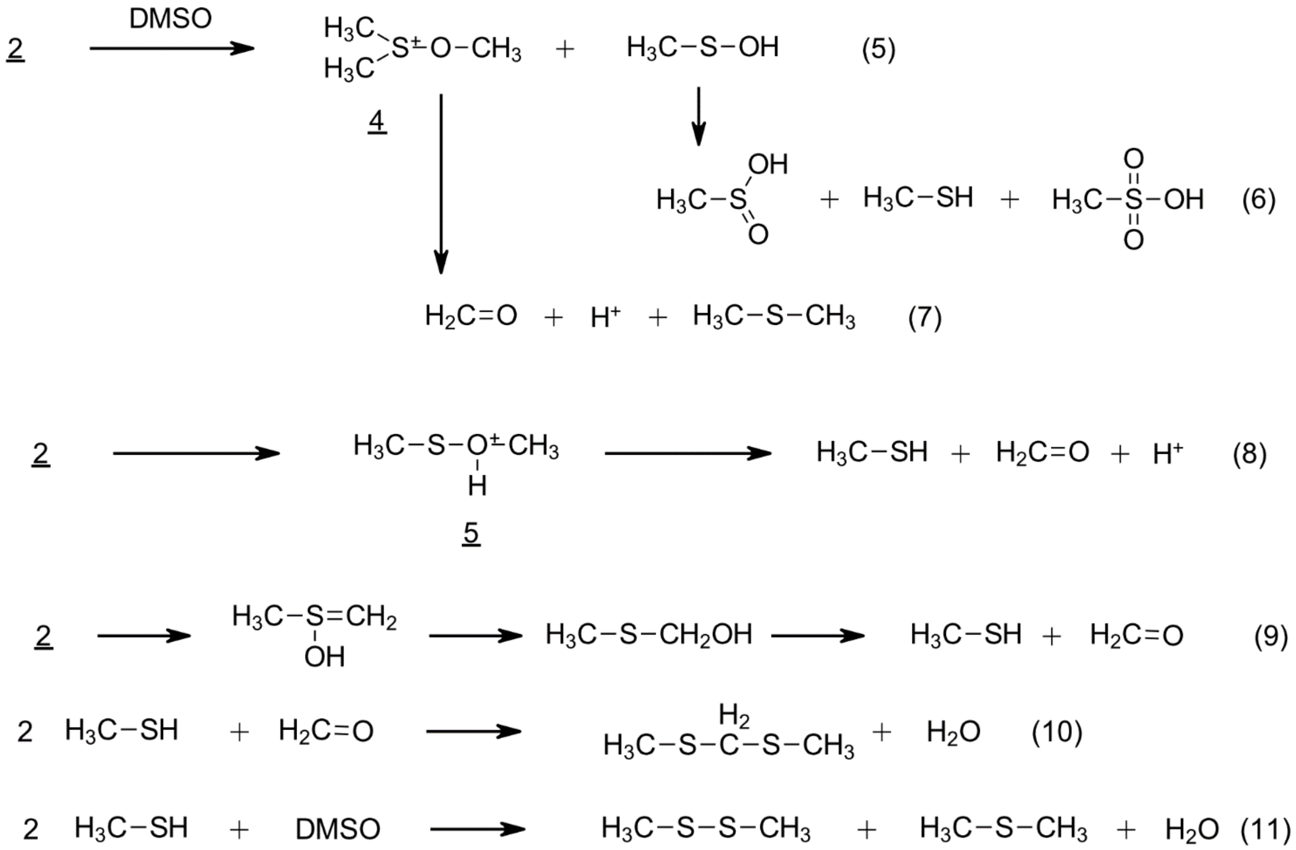
These authors assumed the formation of radical cation 1 followed by the formation of intermediate dimethyl sulfonium cation 2 and radical 3 by reacting 1 with an additional DMSO molecule.



$$(CH_3)_2SO + O_2 \longrightarrow \underset{\underline{1}}{H_3C-\overset{\overset{O}{\|}}{\underset{\bullet+}{S}}-CH_3} + O_2 \qquad (3)$$

$$\underline{1} + (CH_3)_2SO \longrightarrow \underset{\underline{2}}{H_3C-\overset{OH}{\overset{|}{S^{+}}}-CH_3} + \underset{\underline{3}}{\bullet H_2C-\overset{\overset{O}{\|}}{S}-CH_3} \qquad (4)$$

Numerous subsequent reactions of 2 were considered as follows:



$$\underline{2} \xrightarrow{DMSO} \underset{\underline{4}}{(H_3C)_2S^{+}-O-CH_3} + H_3C-S-OH \qquad (5)$$

$$H_3C-S-OH \longrightarrow H_3C-S(=O)-OH + H_3C-SH + H_3C-\overset{\overset{O}{\|}}{\underset{\underset{O}{\|}}{S}}-OH \qquad (6)$$

$$\underline{4} \longrightarrow H_2C=O + H^+ + H_3C-S-CH_3 \qquad (7)$$

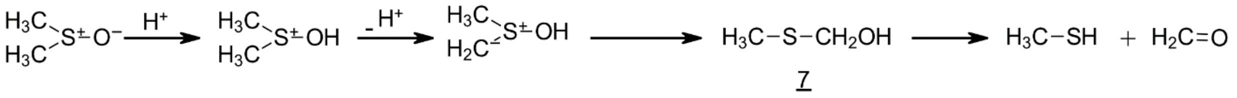
$$\underline{2} \longrightarrow \underset{\underline{5}}{H_3C-S-\underset{\underset{H}{|}}{O^{+}}-CH_3} \longrightarrow H_3C-SH + H_2C=O + H^+ \qquad (8)$$

$$\underline{2} \longrightarrow H_3C-\underset{\underset{OH}{|}}{S}=CH_2 \longrightarrow H_3C-S-CH_2OH \longrightarrow H_3C-SH + H_2C=O \qquad (9)$$

$$2\ H_3C-SH + H_2C=O \longrightarrow H_3C-S-\overset{H_2}{C}-S-CH_3 + H_2O \qquad (10)$$

$$2\ H_3C-SH + DMSO \longrightarrow H_3C-S-S-CH_3 + H_3C-S-CH_3 + H_2O \qquad (11)$$

Santosusso and Swern[58] realized acid formation in the thermolysis of DMSO, although no detailed identification data regarding the acids were provided. They proposed a DMSO decomposition scheme as follows:


(12)

These two research groups individually proposed protonated DMSO **2** with subsequent reaction schemes to give MM and formaldehyde from methylthiomethanol 7, although they differed in the formation process of protonated DMSO **2**. No evidence data to support the reaction schemes were presented in their publications.

Zaraiskii et al.[106] carried out a transformation of DMSO into bis(metylsulfanyl)methane using acetic anhydride in a high yield. They regarded such reaction as Pummerer rearrangement. In reviewing prior studies, they assumed hemithioacet al. as an intermediate which gives rise to a formation of MM and formaldehyde

In the repeated isothermal heating test using an accelerating rate calorimeter (ARC), we observed opacity or turbidity in the resulting liquid. This turbidity was emphasized when water was added to the liquid. We also observed a white deposit on the inner walls of the headspace. In the first half of this section, analyses of these intermediate substances obtained in the induction period are described.

4.5.1 Experimental section

4.5.1.1 Isothermal heating test to collect intermediate substances in the

liquid phase.

The isothermal heating test was carried out to collect intermediate substances using ARC, and the detailed experimental conditions are as follows. For ARC, a THT EURO ARC was used. Isothermal heating was conducted in a nitrogen atmosphere at 185 °C. The sample bomb used was made of SUS316, and the sample amount was 3.0 g.

Isothermal heating was terminated at 55 hours, where only a slight pressure increase was observed. This sampling point was still in an induction period plateau, whereas the temperature quickly increased above 250 °C and the pressure increased by nearly 10 MPa in the short term once the runaway reaction began. After cooling the ARC, the resulting liquid was transferred to a glass screw-cap vial in a nitrogen glove box. The vial was stored at -20 °C before subsequent analyses.

4.5.1.2 Sampling and Analysis of Intermediate Substances in the Liquid Phase.

The content of the screw-cap vial was poured into a 10-fold volume of water and stirred. The solid particles were collected by ultracentrifugation, the supernatant was removed, and the precipitate was dried under a gentle stream of nitrogen.

IR measurements were performed using an FTS3000MX Digilab FT-IR combined with a Digilab UMA600 microscope and operated at a resolution of 4 cm^{-1} in the range of 4000~550 cm^{-1}.

The precipitate was also subjected to LC-TOF-MS analysis. For LC, a Shimadzu Nexera X2 UHPLC equipped with an ODS column was used, and a gradient mobile phase consisting of water/acetonitrile was applied. For the MS detector, a compact Bruker Daltonics was utilized with positive electrospray ionization (ESI+) covering a mass range of 25-1500 Da. The precipitate was dissolved in chloroform and diluted with a ten-fold volume of methanol immediately before injection.

A Bruker Avance NEO 700 was used for nuclear magnetic resonance (NMR) spectroscopic analyses with chemical shift calibration using DMSO-d6 as an external standard. The precipitate was analyzed with ^{1}H-NMR.

4.5.1.3 Sampling and Analysis of the Deposited Substance in the Headspace.

A white deposited substance on the inner wall of the headspace was collected and directly subjected to IR analysis. IR spectra were recorded by a Bio-Rad IR instrument utilizing KBr pellets.

4.5.2 Results and discussions

4.5.2.1 Intermediate substances in the liquid phase.

The IR spectrum of the intermediate substance is shown in Figure 17. Broad and strong peaks at approximately 3400 cm^{-1} were assigned to O-H stretching. These bands were large in comparison to other peaks, suggesting that the water added during the precipitation process remained in the precipitate. Peaks at 1020 and 950 cm^{-1} were assigned to S-O stretching.

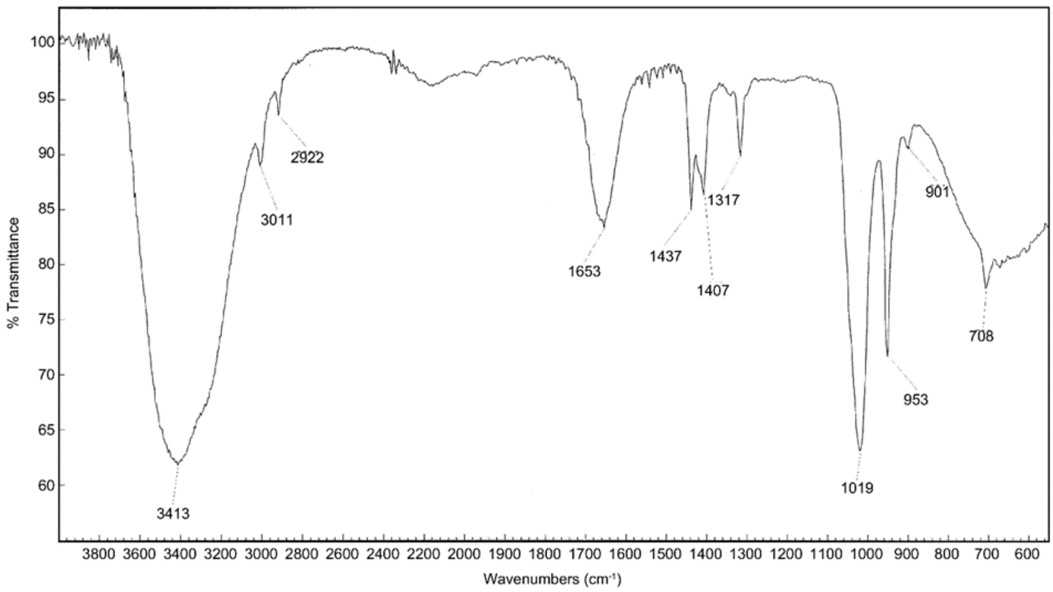


Figure 17. IR spectrum obtained for the observed precipitate.

The spectrum resembled that of DMSO, except in two areas: i) a broad and strong peak was observed at 1650 cm^{-1}, which was not present in the DMSO spectrum, and ii) methylene (CH2) and methine (CH) peaks appearing in the range of 2900-3000 cm^{-1} were smaller than those in the DMSO spectrum.

According to Cairns et al..,29 the addition of water to DMSO results in the υ(SO) shifting to a lower frequency to give a new band at 1650 cm^{-1}. Thus, observation i) may be attributed to the presence of water and DMSO.

The LC chromatogram obtained for the precipitate is shown in Figure 18. Peaks observed at 1.0, 1.3 and 1.5 min were subjected to subsequent TOF-MS analysis, and the results are summarized in Table 7. Since all substances had poor retention in the column, optimal peak separation was not achieved.

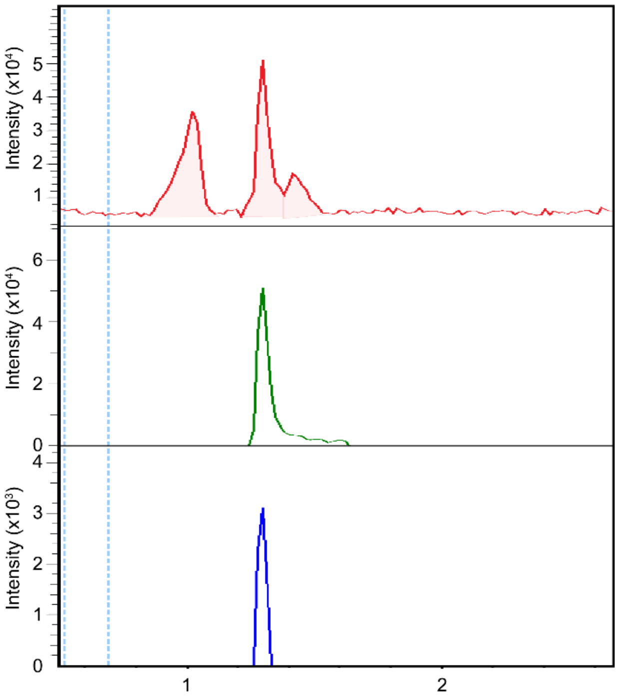


Figure 18. LC chromatogram obtained for the precipitate.

Top: Total Ion Chromatogram

Middle: Selected Ion Chromatogram m/z 79.0214

Bottom: Selected Ion Chromatogram m/z 157.0350

Table 6. TOF-MS Analytical Results Obtained for the Precipitate.

#	Detected Ion (m/z)	Estimated Ion Formular	Estimated Composition
1	226.9513	$[M+H]^+$	$C_5H_7O_4S_3$
2	79.0214	$[M+H]^+$	C_2H_7OS
2	130.1591	$[M+H]^+$	Unknown
2	157.0345	$[2M+H]^+$	C_2H_7OS
3	192.1594	$[M+H]^+$	Unknown

In general, ESI+ mode of LC-MS, a molecular ion is observed in a protonated form, such as $[M+H]^+$ and sometimes $[2M+H]^+$. Peak #2 consists of several fragments due to insufficient chromatographic separation, and an ion with m/z 79.021 was tentatively assigned to the protonated form of the target molecule $[M+H]^+$, while another ion with m/z 157.035 was tentatively assigned to the protonated dimer $[2M+H]^+$ according to known ionization rules. Through these mass analyses, it was found that a target molecule M in peak #2 had a chemical composition of C_2H_6OS, which was identical to that of DMSO. Since the precipitate was separated from a mother liquor consisting of DMSO/water, target molecule M is not likely to be DMSO but a structural isomer thereof.

Precise mass spectrometric analyses were carried out for other peaks in the same way. The chemical composition of peak #1 was tentatively determined to be $C_5H_6O_4S_3$, but no reasonable structural formula was obtained. Similarly, no reasonable composition was obtained for either the ion with m/z 130.1591 or peak #3. Although TOF-MS analysis provided limited information, it was noted that a structural isomer of DMSO was found in the precipitate.

Constructing a practical structural formula with a composition of C_2H_6OS was limited. Twelve possible structures, including that of DMSO, were drawn using a function of SciFindern ®.[107] These are shown in Figure 19.

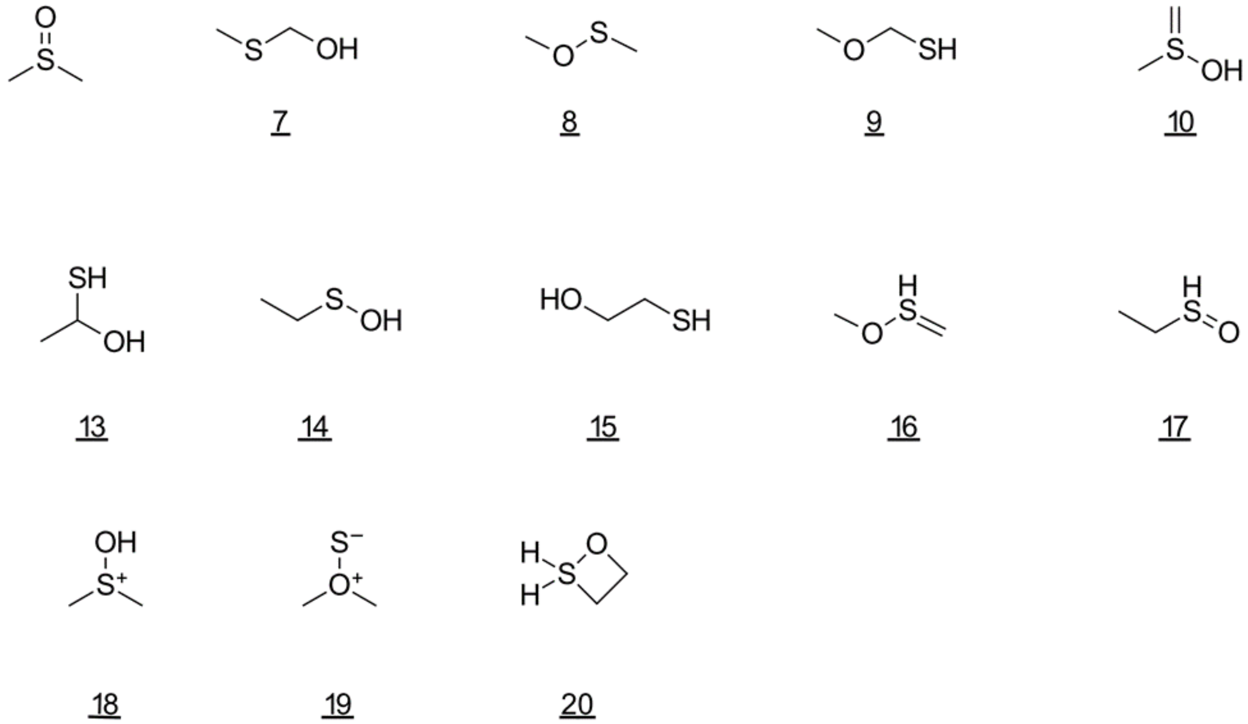


Figure 19. Possible structural isomers having a chemical composition of C_2H_6OS.

Some of the structures seemed energetically unfavorable due to their charge separation or small ring structures. Several others seemed to require too many recombinations in structure to construct an isomer, especially the formation of C-C

bonds, which is energetically unfavorable. As a result, only the four candidates shown below were selected.

The ^{1}H-NMR spectrum for each structure was predicted using a tool developed by Yuri Binev and Joao Aires-de-Sousa at the FCT-Universidade NOVA de Lisboa and is available at nmrdb.org.[108]

Experimentally recorded spectra are shown in Figure 20, and the predicted results are compared in Table 8.

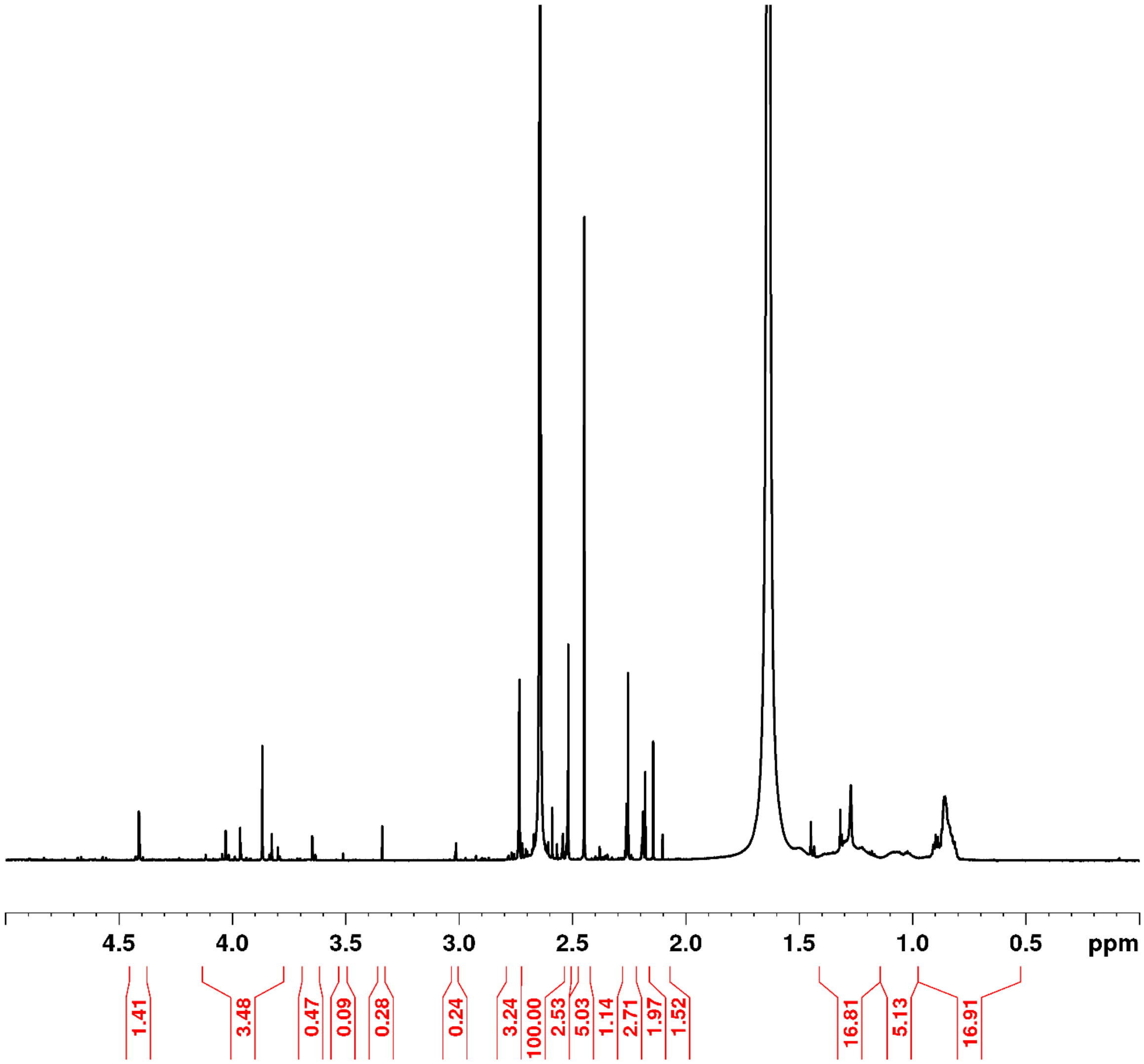


Figure 20. ^{1}H-NMR spectrum recorded for the precipitate (enlarged spectrum).

In peak assignment, several terms should be considered. i) The target substance may not be a major component in the sample. In other words, contaminants such as DMSO appeared on the same spectrum; ii) Experimental ^{1}H chemical shifts can deviate from the predicted signal by 0.1-0.2 ppm; and iii) Certain peak integral ratio shall be obtained between the functional groups reflecting the molecular structure, unless otherwise contamination takes place.

Table 7. Predicted ^{1}H-NMR Spectra for Four Candidate Molecules and Matching Probabilities.

#	Predicted ^{1}H-NMR signals and matching probabilities toward measurement
7	δ 2.14 (3H, s, HP), 4.54 (2H, s, P)
8	δ 2.68 (3H, s, HP), 3.69 (3H, s, U)
9	δ 3.25 (3H, s, U), 4.58 (2H, s, I).
10	δ 3.04 (3H, s U), 5.83-5.87 (2H, 5.85 (d, J = 4.7 Hz), 5.85 (d, J = 4.7 Hz), I).

Labile protons such as OH and SH are not considered here. Matching probability is classified into four classes as follows: (HP), highly probable; (P), probable; (U), uncertain; (I), improbable.

For example, data for candidate **7** were analyzed as follows: peaks at approximately 2.1-2.3 ppm in Figure 20 were assigned to CH_3S-, which was the signal of the first half of molecule **7**, while the peak at 4.4 ppm may be attributed to -CH_2-O- though a slight peak shift toward a higher magnetic field was observed.

For candidate **8**, the CH_3S signal potentially met the experimental requirements, as a strong peak was observed at approximately 2.6 ppm. Although this peak may overlap with some contaminants, no corresponding peak was observed at approximately 3.7 ppm. A peak at 3.65 ppm was observed and expected in terms of the chemical shift, but its intensity was relatively low.

For candidate **9**, the CH_3O- signal expected at 3.25 ppm appeared at 3.33 ppm; however, no peak was observed corresponding to O-CH_2-S. Finally, the CH_3S- signal in candidate **10** was tentatively attributed to a peak at 3.02 ppm in the experimental spectrum, but the terminal vinyl group =CH_2 was not found at approximately 5.8-5.9 ppm.

Labile protons such as OH and SH are not considered here. Matching probability is classified into four classes as follows: (HP), highly probable; (P), probable; (U), uncertain; (I), improbable.

Among the four candidates above, formulae **9** and **10** were inconsistent with the experimental ^{1}H-NMR spectrum and were eliminated. It was difficult however to determine whether formula 7 or 8 showed a better match to the experimental data.

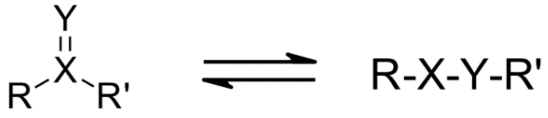
Methylthiomethanol, **7**, corresponds to a product of the Pummerer Rearrangement of DMSO. Pummerer Rearrangement is an acid-catalyzed intramolecular reduction of sulfoxides that leads to the reduction of S(IV) to S(II).[109]

Several authors[2,56,78] described the formation of methylthiomethanol **7** in DMSO decomposition; however, no identifying data has been provided. The reason for this lack of data is likely due to the instability of methylthiomethanol **7**.

Dimethylsulfenate (formula **8**) was prepared by Chen et al.[110] by UV photon-induced isomerization of DMSO in a low-temperature solid argon matrix. The photochemistry of DMSO was derived through radical pathways.

A general rule of thumb regarding isomerization between alkyl sulfenate and sulfoxide was suggested by Wolfe and Schlegel.[18] According to these authors, structure **12** is dominant in a tautomerism equilibrium of **11** ↔ **12** in the liquid phase. However, DMSO, where (X, Y) = (S, O), was an exception, and dimethylsulfenate readily undergoes rearrangement to form DMSO. The authors suggested that dimethylsulfenate had never been observed in the solution.

By considering the reaction conditions to obtain the precipitate, formula *7* shows the best match to an intermediate. It seems rational to conclude that Pummerer Rearrangement takes place even in DMSO during the decomposition induction period to give methylthiomethanol **7**.



(13)

11

12

When focusing on the relationship between the peak area ratio and chemical composition of methylthiomethanol **7**, peaks assigned to CH_3S- were larger than corresponding methylene peaks in $-CH_2OH$; this was probably due to a contaminant carrying only CH_3S- as a partial structure, such as MM (CH_3SH) and DMS (CH_3SCH_3).

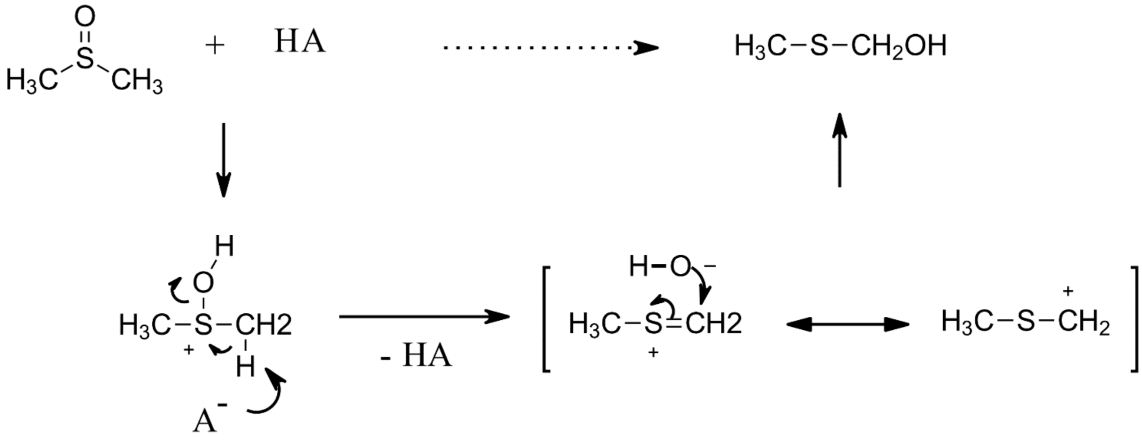


Figure 21. Pummerer Rearrangement

Synthesis of methylthiomethanol 7 has not yet been documented probably due to its poor stability. However, methylthiomethyl (MTM) seters have been utilized as protecting groups for carboxylic acids.[111] t-Butyl bromide was found to be a particularly effective ‘activator’ of dimethyl sulphoxide in reactions with nucleophiles.[112] The traditional route for converting carboxylic acids to MTM esters involve treating carboxylic acids with t-butyl bromide in DMSO. An intermediate $CH_3\text{-}S^+\text{=}CH_2$ is assumed in this process. McCarthy et al.[113] developed a direct method using a microwave-assisted Pummerer Rearrangement.

As a consequence of the Pummerer type reactions, sulfoxide is cleaved by acid, resulting in the reduction of the sulfur atom from (4) to (2).[114-116]

4.5.2.2 Deposited material.

Several authors reported that DMS and formaldehyde were formed together in the early stages of DMSO decomposition.[55,105] The ATR spectrum of the deposited substance is compared to that of polyacetal. resin in Figure 22. As reported by the prior studies, the two spectra resemble each other except that the deposited substance has a very broad O-H stretching band at 3100-3700 cm^{-1}. It was clear that the deposited substance mainly consisted of polyformaldehyde.

There are two kinds of polyformaldehyde: a linear polymer (paraformaldehyde) and a cyclic trimer (1,3,5-trioxane). Trioxane is a low-molecular-weight, crystalline compound (mp: 64 °C and bp: 114.5 °C), while paraformaldehyde is a polymeric material having no vapor pressure.

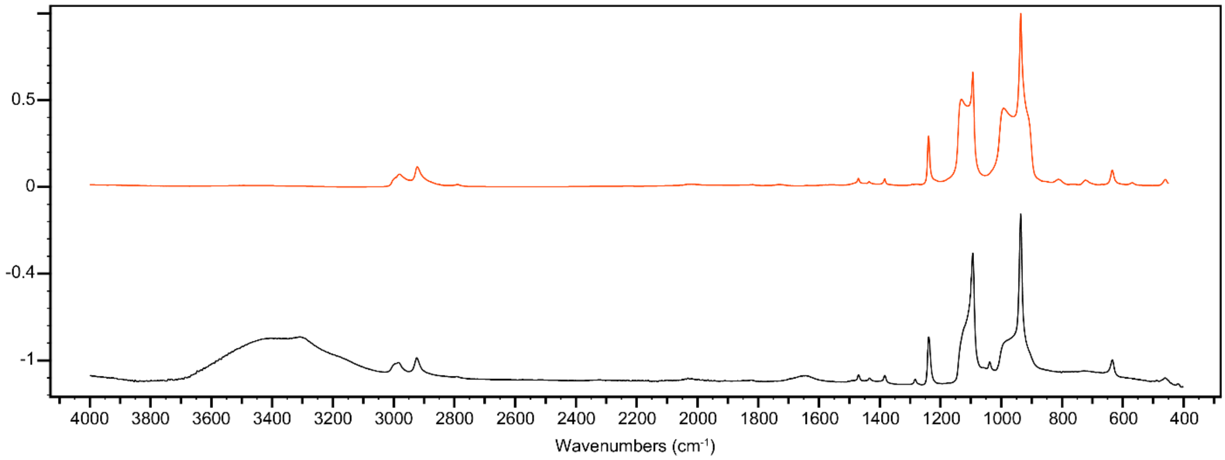


Figure 22. ATR spectrum of the deposited substance.
Upper: polyacetal resin (Reference), Lower: deposited substance

To identify whether the deposit was trioxane or paraformaldehyde, ^{1}H-NMR analysis was performed, as shown in Figure 23. A sharp peak at 9.8 ppm was assigned to monomeric formaldehyde, and peaks at approximately 5 ppm were assigned to methylene (-CH_2-) protons in paraformaldehyde. A very small peak at 5.15 ppm was tentatively assigned to trioxane; however, most of the polyformaldehyde was not in the form of trioxane but in the form of paraformaldehyde. Formaldehyde was proposed to be vaporized first and polymerized in the headspace of the ARC vessel.

It should be noted that a small peak at 8 ppm was attributed to FA according to a chemical shift. Some portion of formaldehyde seemed to be oxidized to form FA. The labile intermediate methylthiomethanol 7 may be proposed to be a precursor of formaldehyde, as well as FA.

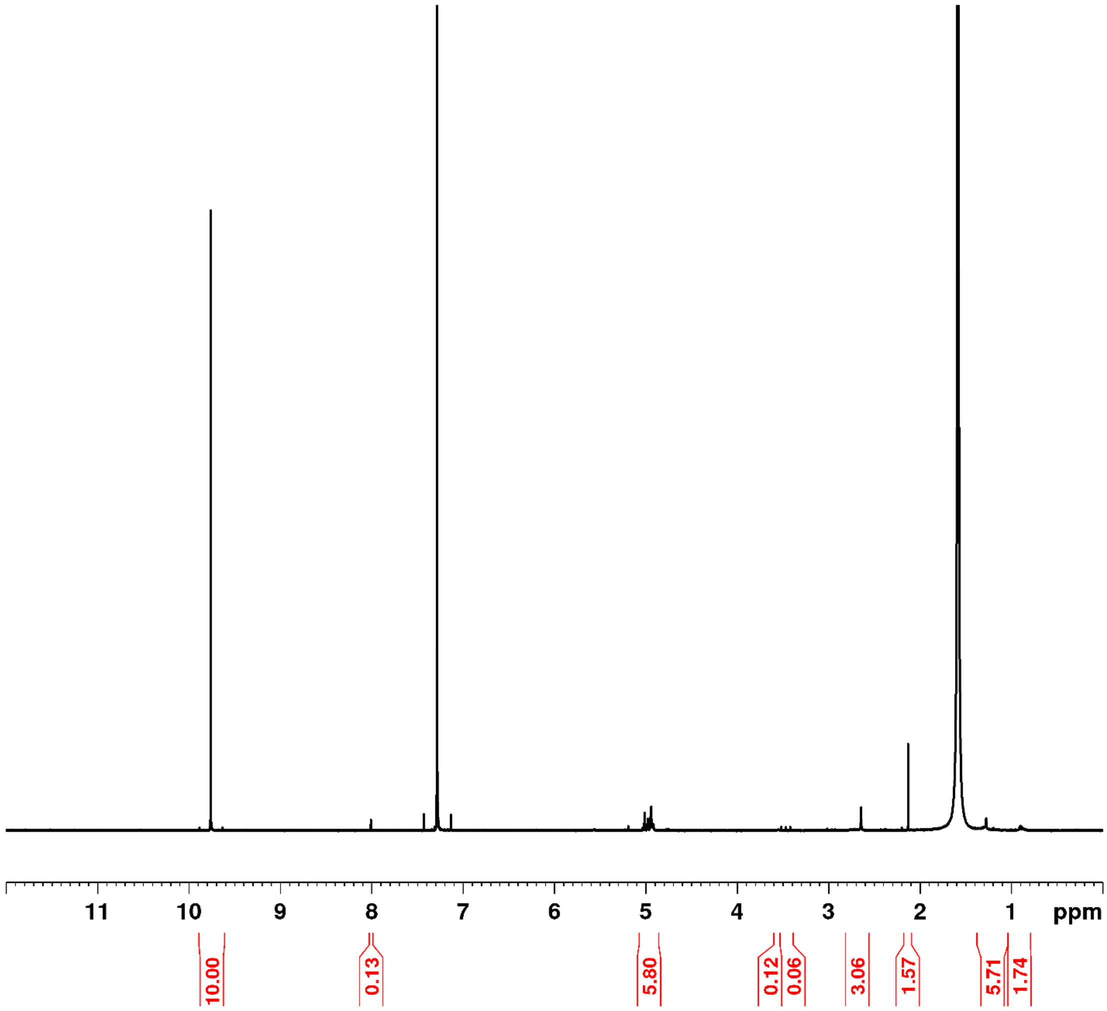


Figure 23. ^{1}H-NMR spectrum recorded for the deposited substance.

4.5.3 Hypothesis regarding the initial part of decomposition

The discovery of the formation of methylthiomethanol **7** during the induction period gave rise to an interesting hypothesis regarding the initial part of decomposition. Prior studies have explained that DMSO decomposes into MM and formaldehyde as shown in Eq. 14 in the early stages of DMSO deecomposition. Li et al,[117] proposed an unusual but interesting synthetic method to use a combination of DMSO and HCl as an equivalent of formalodehyde. Lin et al.[118] found that formaldehyde detected in the headspace GC using DMSO as a sample diluent is an artifact resulting from decomposition of DMSO.

The formation of MM and formaldehyde was confirmed in this study as well, and supports to some extent the viewpoint of mass balance.

However, activation energy (*Ea*) of this reaction is extremely high according to the quantum calculation., and the validity of Eq. 14 has been questioned by Koizumi.[119] On the other hand, a relatively small Ea wais obtained when Eq.15 was examined by Watanabe et al. using quantum calculation, and this reaction was considered to proceed via methylthiomethanol **7**.[120]

In this section, it is explained that DMSO undergoes Pummerer Rearrangement to generate methylthioethanol **7** under acidic conditions in the induction period. As DMSO and methylthiomethanol are the structural isomers with the same composition, we can hypothesize that the overall reaction is likely not to proceed directly, but to proceed via methylthiomethanol **7**. Detailed examination and verification will need to be carried out to confirm this hypothesis in the near future.

$$\text{DMSO} \xrightarrow{\times} CH_3SH + HCHO \quad (14)$$

$$CH_3SCH_2OH \rightarrow CH_3SH + HCHO \quad (15)$$

$$\mathrm{DMSO} \rightarrow \mathrm{CH_3SCH_2OH} \rightarrow \mathrm{CH_3SH} + \mathrm{HCHO} \quad (16)$$

4.5.4 Brief conclusion of this section

In the first half of this section, analyses of intermediate substances found in the induction period were carried out. Methylthiomethanol 7 was found to be one of the intermediates in the liquid phase. It was proposed that Pummerer Rearrangement took place under acidic conditions in the induction period.

In the second half, and formaldehyde and its derivatives were found in the deposited material in the headspace.

The interesting findings were as follows:

i. LC-TOF-MS analysis revealed that intermediate substances in the liquid phase contained a structural isomer of DMSO.
ii. The structural isomer was identified to be methylthiomethanol 7, which corresponds to a product of Pummerer Rearrangement under acidic conditions.
iii. Deposited substances in the headspace consisted of formaldehyde, polyformaldehyde and a small portion of FA. Polyformaldehyde was not present as a cyclic trimer but as paraformaldehyde.
iv. The formation of methylthiomethanol 7, formaldehyde and FA may be sequential.

It should be noted that a small peak at 8 ppm was attributed to FA according to a chemical shift. Some portion of formaldehyde seemed to be oxidized to form FA. The labile intermediate methylthiomethanol 7 may be a precursor of formaldehyde as well as FA

4.6 Behavior of formic acid and its effect on thermal decomposition

As descrived in §4.3, the acid concentration increased over heating-time during the isothermal heating test.[99] Among the acids found, formic acid (FA) showed a higher concentration than that of any other acids at all sampling points. In addition, FA showed a larger effect than methanesulfonic acid or sulfuric acid on shortening the induction period. It is proposed that FA plays a key role in the autocatalytic decomposition of DMSO.

One simple research question surfaced: “Why does FA accumulate in DMSO during isothermal heating at 185 °C? FA has a bp of 100.8 °C, which is much lower than that of DMSO. Therefore, FA should be vaporized first and removed from liquid DMSO.”

DMSO exhibits heat evolution when solvated with polar solvents carrying active hydrogen atoms, such as water and alcohol. Fink et al.[46] observed heat evolution in the FA/DMSO system and suggested that sources for the heat evolution were the protonation of DMSO and liberated solvation energy.

Another behavior was reported by Yoshimura and Utsumi.[121] These authors developed a new class of acid derivatives with low acid vapor pressures for the purpose of elemental analysis. They prepared dry gaseous HCl , and introduced it into dried DMSO to obtain a white precipitate. The filtered precipitate was washed with ether, and then air dried. In similar fashion, they prepared several equimolar adducts consisting of DMSO-inorganic acid or DMF-inorganic acid. The melting points of the adducts were much higher than those of their original acids. It is clear that the adducts showed much higher bp values than those of their free acids. We hypothesized that FA generated in situ was stabilized by solvation with DMSO.

On the other hand, James et al.[122] were first to demonstrate crystallographically through the solvation of protons in DMSO solvent resulting in the formation of a hydrogen bonded cation [Me2S=O···H···O=SMe2]+ with a bridging proton. Denisov. et al.[123] confirmed the 2:1 complex of DMSO-HCl. Rudniitskaya et al[124.] recently reported the presence of monoprotonated DMSO in Os salt in the solid state. Mixtures of FA/DMSO with various ratios were prepared to investigate their vaporization behaviors.

In addition to the dissolved state of FA in DMSO, the effect of FA on DMSO decomposition is important information for safety management. Babasaki et al.[75] studied the influence of organic acids on the thermal stability of DMSO by choosing several organic acids with different pKas. Since they prepared mixtures consisting of DMSO and organic acids with a ratio of 10:1 (mole), a wider concentration range was covered. The FA concentration at the turning point seems to be important, and it is estimated several thousand ppm based on our previous study. Thus, our attention was paid to low concentrations of FA in particular.

The behaviors and effect of FA on DMSO decomposition are discussed in the second half of this section.

4.6.1. Experimental section

4.6.1.1 Preparation of FA/DMSO mixture.

Various ratios of FA/DMSO mixtures were prepared in plastic bottles. A concentrated mixture of 10:90 FA/DMSO (mole ratio) was utilized to precisely prepare a lower concentration solution.

The headspace of each sample bottle was purged with nitrogen gas, and the bottle was placed in the refrigerator for measurement.

4.6.1.2 Low-temperature DSC characterization of FA/DMSO mixture.

FA/DMSO (50:50, mole ratio) underwent neither crystallization nor precipitation even after overnight storage in a freezer at -20 °C. Low-temperature differential scanning calorimetry (DSC) measurements using liquid nitrogen were applied to determine the freezing point. For DSC, a Hitachi High-Tech Science DSC7000X instrument was used. A portion (5 mg) of FA/DMSO was poured into an aluminum pan, and the pan was cooled from room temperature to -150 °C at a constant rate of -10 °C/min. The pan was then subjected to heat, and the raised to room temperature at an inversely proportional rate.

For reference purposes, 50:50 acetic acid/DMSO (mole ratio) was also subjected to low-temperature DSC measurements.

4.6.1.3 GC-MS analysis of FA/DMSO mixture.

GC-MS analysis was carried out on a 50:50 FA/DMSO (mole ratio) solution to investigate the association of FA/DMSO. GCMS experimental conditions were as follows. For GC-MS, an Agilent Technologies 6890N instrument combined with a 5975 inert unit was implemented. Separation was achieved on an Agilent DB-WAX column (0.25 mm ID, 30 m, 0.25 μm layer thickness). The temperature program of the column oven was held at 40 °C for 5 minutes, increased 20 °C/min until a temperature of 260 °C, and was held for 10 minutes. The injection temperature was 150 °C, and helium (1 mL/min) was used as the carrier gas. A split ratio of 1/100 was utilized with split injection mode. The temperatures of the interface and ionization chamber were set to 250 °C. The EM voltage was 1000 eV.

Two dilute FA/DMSO solutions (0.1 wt% FA and 0.5 wt% FA) were prepared and subjected to headspace GC-MS analysis. A small portion (300 µL) of each mixture was added to a headspace vial, and the closed vial was placed in an oven at 145 °C. The gas phase of the vial was sampled at 0.5, 3 and 6 hours and analyzed using GC-MS equipped with a head-space gas sampler.

The analytical conditions were as follows. For GC-MS, an Agilent GC 7890A was combined with a 5975C inert MS detector. An Agilent DB-FFAP column (0.25 mm ID, 30 m, 0.25 µm layer thickness) was used. The temperature program of the column oven was a 5 min hold at 40 °C (5 min hold) and an increase at 20 °C/min to 250 °C (10 min hold). The injection temperature was 150 °C, and helium (1 mL/min) was used as the carrier gas.

A split ratio of 1/10 was implemented in split injection mode. The interface and ionization temperatures were set to 280 °C and 250 °C, respectively. The EM voltage was 1400 eV.

4.6.1.4 DOSY characterization of the FA/DMSO mixture.

A Varian VNMRS600 instrument was used for diffusion-ordered spectroscopy (DOSY) measurement on a series of FA/DMSO mixtures. The chemical shift was calibrated with tetramethyl silane (TMS) dissolved in $CDCl_3$ as an external standard.

For the pulse program, bipolar-pulse-pairs stimulated-echo with longitudinal eddy current delay (BPP-STE-LED) was used. The experimental conditions were as follows: temperature, 30 °C; diffusion delay, 60 ms; gradient pulse length, 2 ms; gradient strengths, 2.0-49.0 Gauss/cm for 16 points; relaxation delay, 13-26 sec (depending on the sample); and acquisition time, 3 sec.

VnmrJ 4.2 and the DISCRETE algorithm were applied for data analysis. For the window function, line broadening of 2 Hz was used.

4.6.1.5 Thermal decomposition of the FA/DMSO mixture.

Small portions of the FA/DMSO mixture (ca. 1.5 mg) with various mixing ratios were loaded into a high-pressure DSC pan made of SUS303 in a nitrogen glove box to exclude the effect of oxygen. Ramp DSC experiments were carried out on a DSC Q20 (TA Instruments) in the temperature range from 40 to 430 °C at a heating rate of 10 °C/min. Measurements were repeated five times to minimize experimental error.

4.6.2. Results and Discussions

4.6.2.1 Low temperature DSC characterization of FA/DMSO Mixture.

Low-temperature DSC curves recorded for 50:50 FA/DMSO (mole ratio) are shown in Figure 24. The upper curve corresponds to the cooling process from room temperature to -150 °C, while the lower curve corresponds to the reverse heating process. A freezing point was not observed, whereas a phase transition was observed at -128 °C.

This transition behavior was far from ordinary crystallization; instead, it resembled the glass transition phenomena of polymers. A clear melting point was not observed in the upward process. FA/DMSO (50:50, mole ratio) remained in liquid at low temperatures and showed no freezing/melting point.

A 50:50 (mole ratio) mixture of acetic acid/DMSO was another equimolar mixture with similar behavior to that of FA/DMSO, as shown in Figure 25. An equimolar mixture of low-molecular-weight organic acid/DMSO did not freeze even at low temperatures below -100 °C, unlike inorganic acid/DMSO salts.

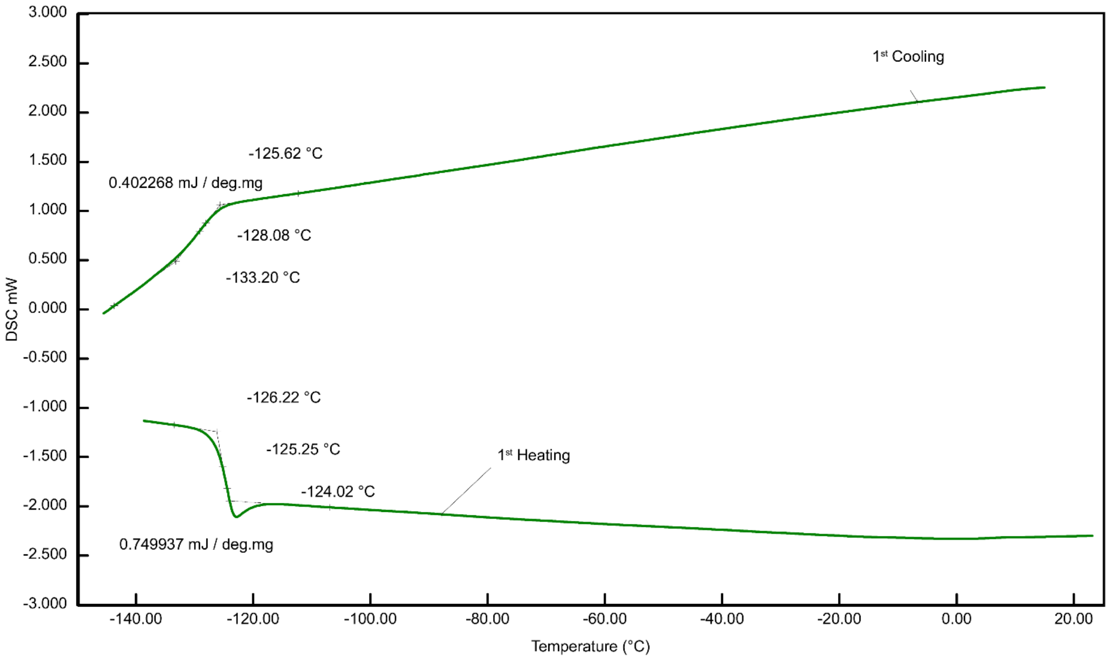


Figure 24 Low temperature DSC recorded for FA/DMSO 50:50 (mole ratio).

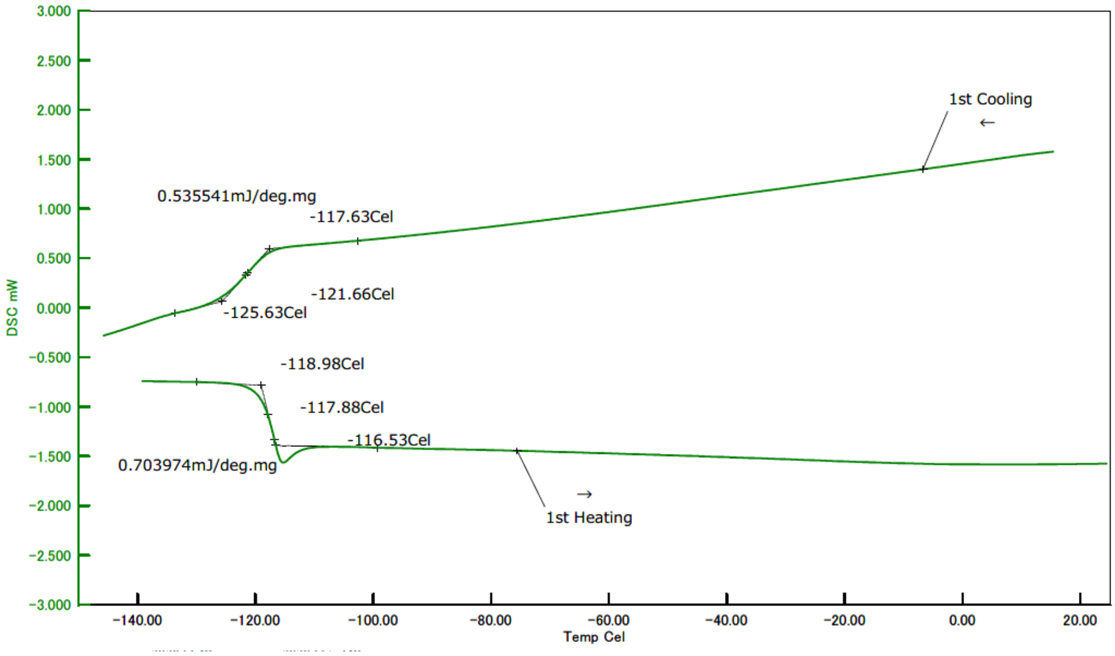


Figure 25 Low temperature DSC recorded for acetic acid/DMSO 50:50 (mole ratio).

Ordinary direct GC-MS analysis was carried out for analysis of 50:50 FA/DMSO (mole ratio), and the chromatogram is shown in Figure 26.

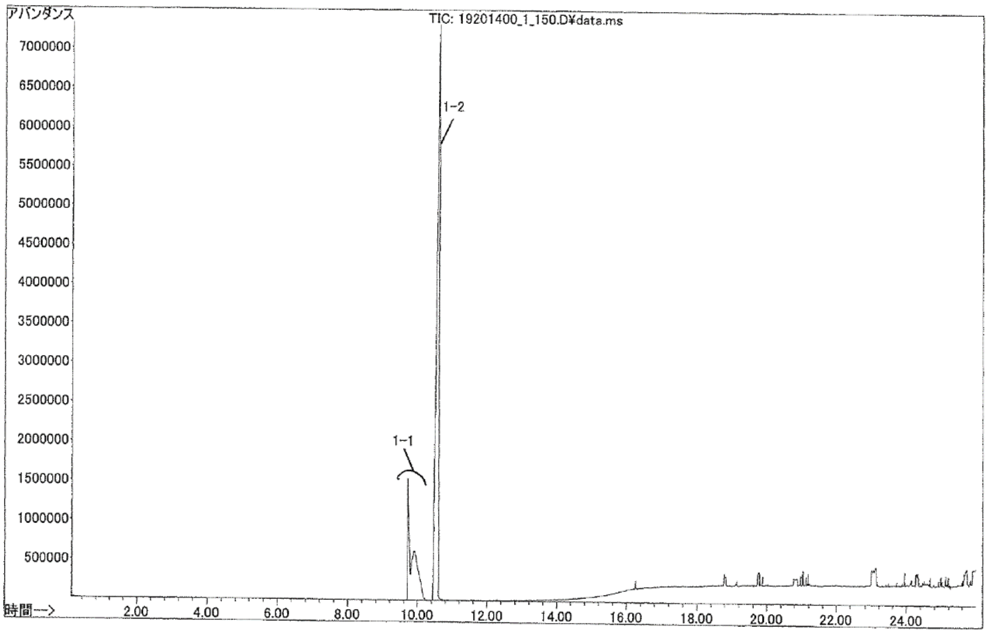


Figure 26. GC-MS chromatogram of FA/DMSO 50:50 (mole ratio).

According to the MS analysis, separate peaks were assigned to FA and DMSO, respectively. The product peak was not observed, even under a situation where a 1:1 association was expected between FA and DMSO. No evidence was obtained for the association of FA and DMSO by direct GC-MS analysis.

4.6.2.2 Specific volatility of FA against DMSO.

In the next attempt, a headspace GC-MS technique was applied for the characterization of the FA/DMSO mixture. Head-space GC-MS is commonly used for the determination of volatile organic compounds such as chlorinated hydrocarbons contained in water. In general, 30 min of heating is sufficient to reach gas/liquid equilibrium at elevated temperatures.

In this study, the specific volatility of FA against DMSO was tentatively defined as the peak area ratio ([FA]/[DMSO]).

The gas phase was taken from the headspace vial at 0.5, 3 and 6 hours at 145 °C, and the specific volatility of FA was plotted against time, as shown in Figure 8. Even after 6 hours, the increasing curve did not reach a constant value, although the oven temperature was set to 145 °C, between the boiling points of the two substances. The specific volatility of FA against DMSO seemed to be suppressed.

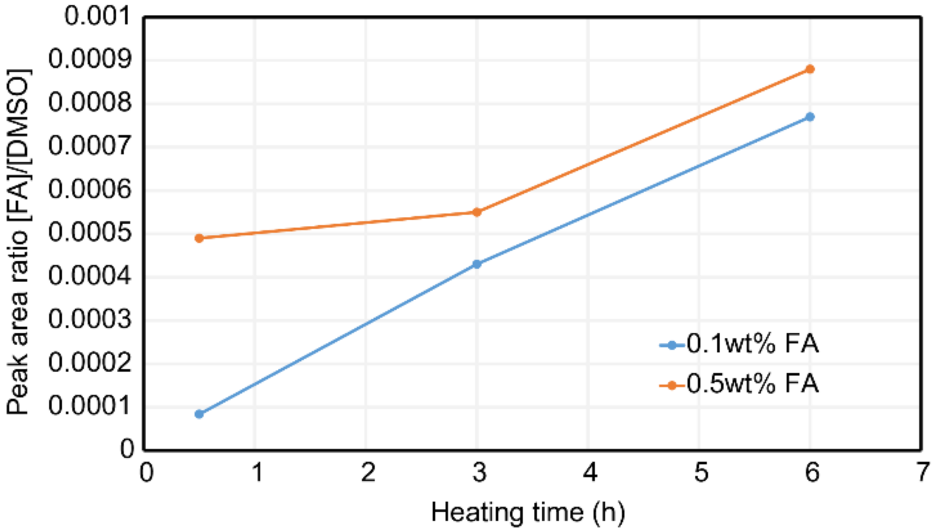


Figure 27 Specific volatility of FA against DMSO.

4.6.2.3 DOSY characterization of the FA/DMSO mixture.

DOSY is a multidimensional NMR technique utilizing a pulse field gradient to separate NMR signals consisting of different species according to their diffusion coefficients.[125] After processing the data, a 2D DOSY display with ^{1}H chemical shifts along the X axis and diffusion coefficients along the Y axis is obtained.

The advantage of DOSY is that signal separation relies not on chromatography but on the NMR pulse technique. Neither thermal decomposition in the GC injection port nor dissociation during column separation in LC takes place. A DOSY NMR approach was applied for the investigation of ionic liquids to utilize these advantages.[67]

Two-dimensional DOSY data recorded for a series of FA/MDSO mixtures are shown in Figures 28-32.

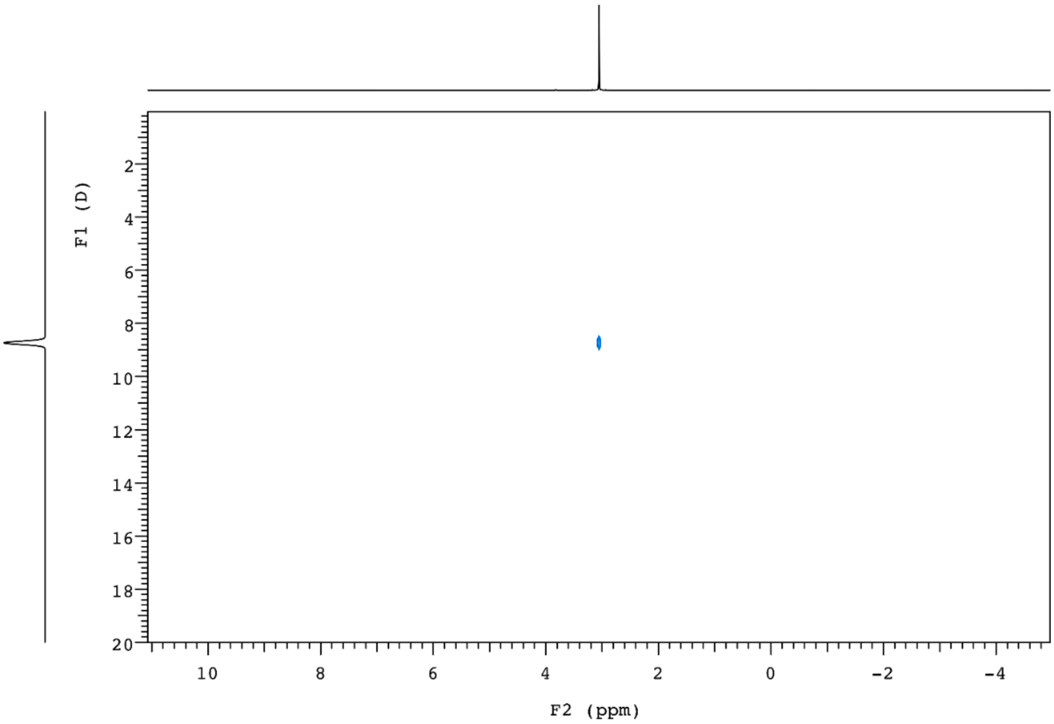


Figure 28 2D DOSY display for 0:100 FA/DMSO (mole ratio).

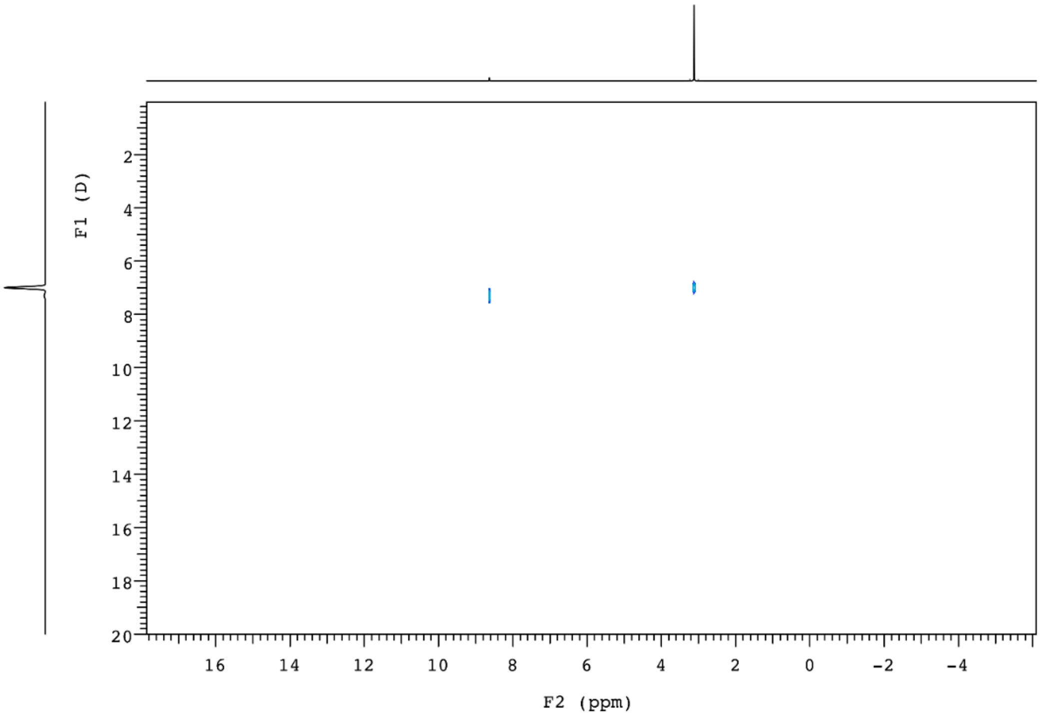


Figure 29. 2D DOSY display for 25:75 FA/DMSO (mole ratio).

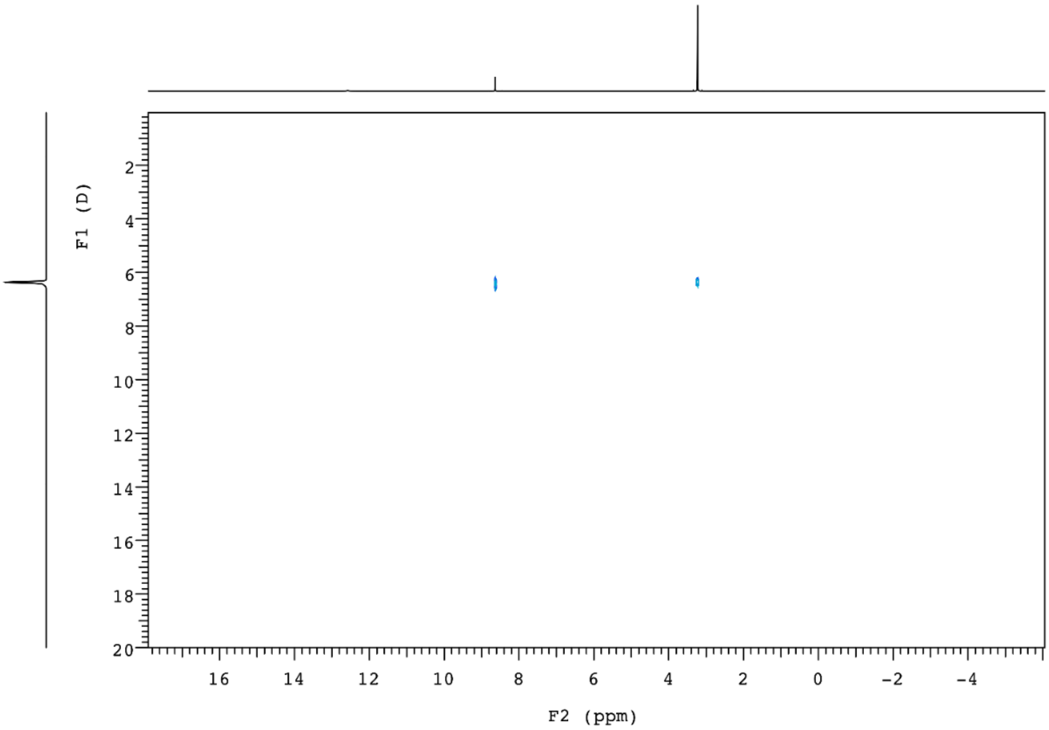


Figure 30. 2D DOSY display for 50:50 FA/DMSO (mole ratio).

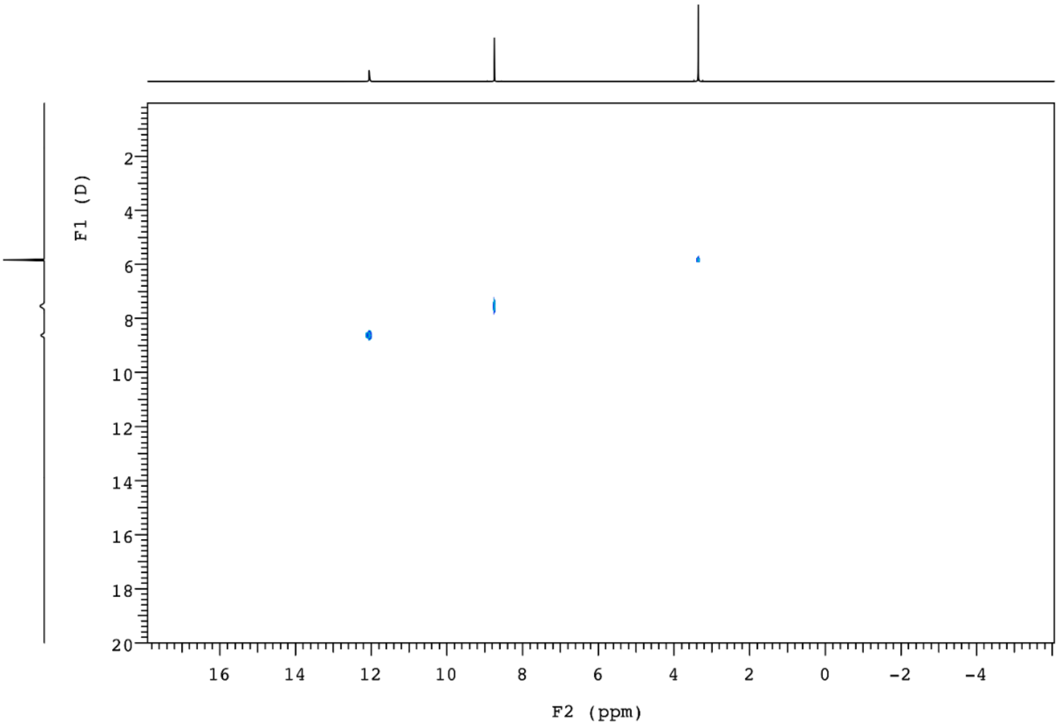


Figure 31 2D DOSY display for 75:25 FA/DMSO (mole ratio).

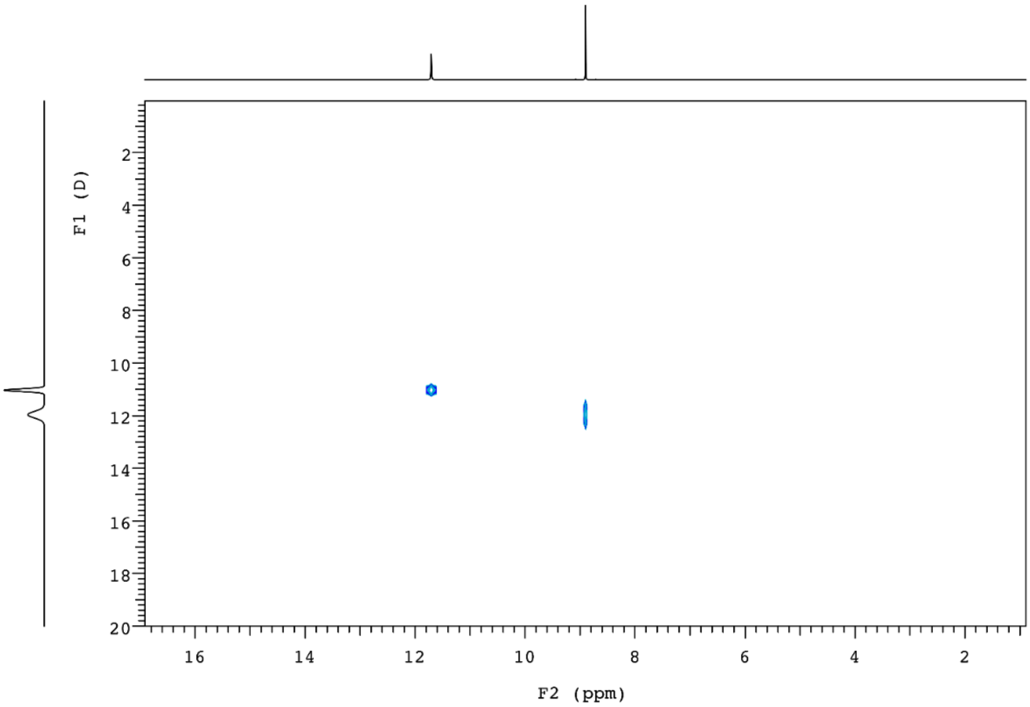


Figure 32. 2D DOSY display for 100:0 FA/DMSO (mole ratio).

Interpretation of DOSY was straightforward in this study. For instance, a DOSY display obtained for pure DMSO showed one cross-peak at 3.06 ppm along the 1H chemical shift (F2, X-axis) and at 8.72 ($\times 10^{-10}$ m^2/s) along the diffusion coefficient (F1, Y-axis), as shown in Figure 27. DMSO has six equivalent protons, and these DOSY results indicated the presence of one structure in neat DMSO.

In contrast to DMSO, FA has two kinds of protons in its molecule: one type of proton includes free protons from carboxylic acid, and the other type includes formyl protons. For example, neat FA shows two cross-peaks, as shown in Figure 31. Free protons appeared at 11.71 ppm, and formyl protons appeared at 8.90 ppm, and these two signals exhibited slightly different diffusion coefficients. The mean signal value was adopted in such a case.

It was interesting that FA and DMSO showed the same diffusion coefficient of 6.40 ± 0.04 in an equimolar mixture of FA/DMSO as shown in Figure 29. This meant that two associated molecules behaved as one molecule. The DOSY results obtained for a series of FA/DMSO mixtures are summarized in Table 8. From the DOSY results, it is clear that FA created an equimolar adduct with DMSO, similar to strong acids.

Table 8. Summary of DOSY Results Obtained for a Series of FA/DMSO Mixtures

Sample	FA (mole)	DMSO (mole)	Diffusion Coefficient FA ($x10^{-10}m^2/s$)	Diffusion Coefficient DMSO ($x10^{-10}m^2/s$)
1	0	100	-	8.72
2	25	75	7.36	6.99
3	50	50	6.44	6.37
4	75	25	7.54	5.83
5	100	0	11.96	-

The shape of the cross-peak in the multicomponent system was also noted. The association of FA with DMSO can be regarded as a sort of acid-base equilibrium. If the exchange rate is fast enough relative to the NMR time scale, the average peak rather than characteristic individual peaks is observed in a spectrum. The DMSO cross-peak appeared as a couple of dots when the molar FA/DMSO ratio was 25:75, as shown in Figure 28. In this case, two separate peaks were observed for DMSO, with that of [DMSO] being much larger than that of [FA]. This was an indication that DMSO had two structures, presumably those with and without FA association, and the exchange rate in equilibrium was relatively slow.

In contrast, DMSO exhibited one dot when the molar FA/DMSO ratio was 75:25, as shown in Figure 30. The shape of the cross-peak in the multicomponent system was also noted. The association of FA with DMSO may be regarded as a sort of acid-base equilibrium.

By combining the results of low-temperature DSC, headspace GC-MS and DOSY, it was plausible to propose that the suppression of FA volatility was due to the association of FA with DMSO.36 An equimolar mixture of FA/DMSO remained liquid at low temperatures below -100 °C; this was certainly a characteristic typical of ionic liquids.[126]

It is important to recognize that FA can be accumulated in the liquid phase of DMSO, although FA has a much lower boiling point. It is reasonable to expect that other acids generated *in-situ* react similarly.

4.6.2.4 Thermal decomposition of the FA/DMSO mixture.

Heat quantities (Q) obtained for a series of FA/DMSO mixtures were plotted against FA content, as shown in Figure 33. The heat quantity of pure DMSO was ca. 550 J/g, which was almost equal to that reported in a prior publication.8 It is interesting and important for safety management that a plot of Q vs FA content exhibits a convex curve on top. Although the reason for this is still uncertain, it is apparent that DMSO decomposition pathways are influenced by the FA content. As a result, a larger Q is generated by the addition of FA. In particular, it should be noted that a 25:75 FA/DMSO (mole ratio) sample shows a very large Q, which is almost twice that of neat DMSO.

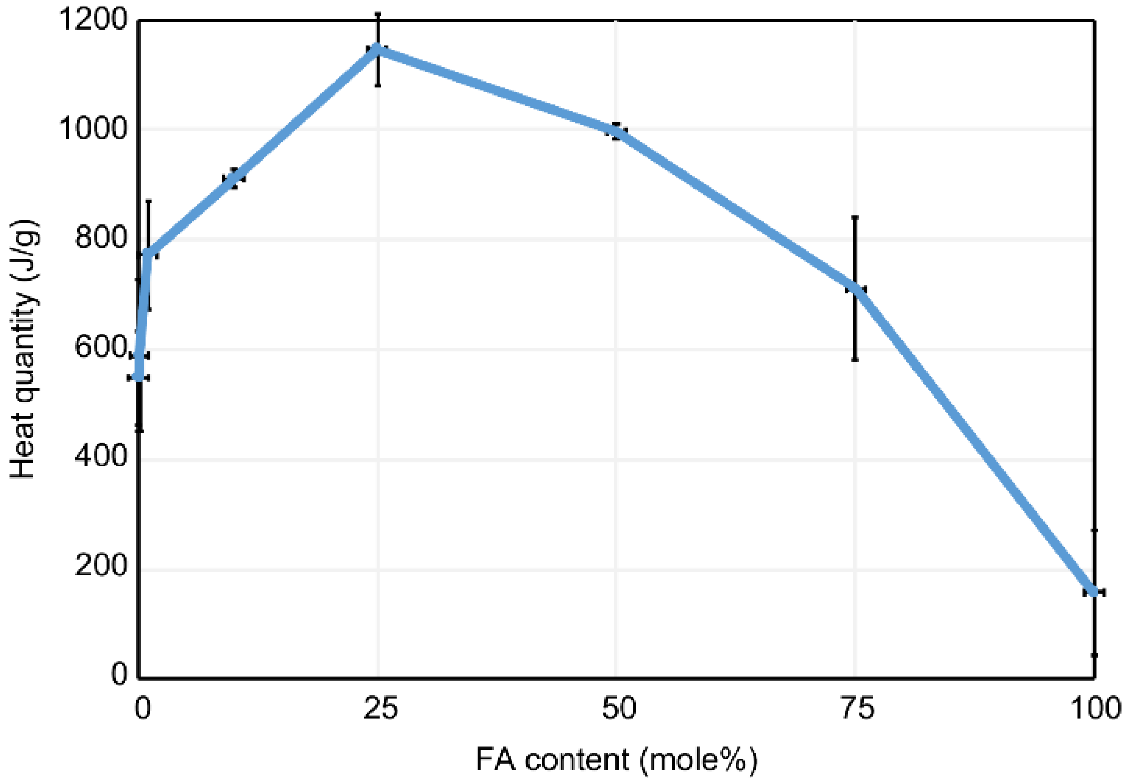


Figure 33. Plot of heat quantity (Q) against FA content obtained for a series of FA/DMSO mixtures.

4.6.3. Brief conclusions of this section

In the previous section, it was found that acids generated in-situ work as autocatalysts to shorten the induction period of DMSO decomposition. In this section, the focus was on several various aspects of FA.

The association between FA/DMSO and its effects on DMSO decomposition were investigated. FA was found to be stabilized by associating with DMSO, which led to a decrease in volatility and to an accumulation of FA in DMSO. From a viewpoint of DMSO safety management and handling, it should be noted that the volatilization of FA is suppressed by its association with DMSO, which leads to undesired accumulation.

In addition, FA largely increases the heat quantity of DMSO decomposition. Although the precise mechanism of enhancing heat quantity is not clear, FA plays a key role in the autocatalytic DMSO decomposition mechanism as well as provides insight for DMSO hazard management.

The notable findings were as follows:

i. FA and DMSO showed the same diffusion coefficient in an equimolar mixture of FA/DMSO, meaning that FA creates an equimolar adduct with DMSO.

ii. The suppression of FA vapor was proposed to be due to the association of FA with DMSO. FA can accumulate in DMSO despite its low boiling point.

iii. DMSO decomposition pathways are influenced by the small addition of FA, and a plot of heat quantity vs FA content exhibited a convex curve.

4.7 Kinetic study regarding main decomposition

4.7.1 Literature review

For safety purposes, it is important to ascertain what type of reaction mechanism takes place during DMSO decomposition. Several acids formed during the isothermal heating of DMSO, even in an inert atmosphere, meet the general definition of autocatalysts.

However, Hall suggested that DMSO decomposition is accelerated by both acids and bases.[59] Yang et al. showed that NaOH reduced the values of ADT_8 and ADT_{24} during DMSO decomposition.[74] Their results seem to contradict the catalytic role of acids in DMSO decomposition.

Cardillo and Girelli[2] stated that DMSO decomposed at its boiling point (189 °C) in the presence of sodium carbonate, and that zinc oxide did not affect the decomposition temperature.[2] These authors reported that DMSO decomposed in air through a non-autocatalytic, a radical-like mechanism. Head and McCarty[29] assumed a radical cation as a decomposition intermediate, followed by a reaction with another DMSO molecule to produce a pair of cations and radicals.

On another front in biochemistry,[127-129] DMSO has been utilized as a trapping and quantifying reagent of hydroxyl radicals (·OH) in aqueous systems. The method is based on the reaction of hydroxy radicals with DMSO to produce methanesulfinic acid and methyl radicals ($\cdot CH_3$), as shown in Eq. 17. DMSO is likely to react with radicals, even at ordinary temperatures. .Gonzalez-Garcia et al. studies the reaction mechanism of DMSO and ·OH theoretically in relation to the atmospheric oxidation of DMSO.[130]

However, no previous studies have investigated similar systems at elevated temperatures,

$$CH_3\text{-}SO\text{-}CH_3 + \cdot OH \rightarrow CH_3\text{-}SOOH + \cdot CH_3 \qquad (17)$$

On the other hand, Herscu-Kluska et al.[131] studied reaction of daricals with peroxides and DMSO, and they claimed the formation of methyl radical ($\cdot CH_3$) in the presence of DMSO was not proof of the formation of hydroxy radical (·OH). The primary research question in this section relates to the reaction mechanism in the main decomposition of DMSO.

The other important safety issue with respect to DMSO is its large exothermic reaction when decomposed. It is a mystery why DMSO exhibits such a vigorous reaction despite not carrying any reactive functional groups, such as multiple bonds, epoxides, nitros, azos and peroxides, in the molecule.

Brandes and Smith[70] reviewed prior literatures and summarized the published data with a comparison of their own data. In this work, the heat quantities of DMSO decomposition are roughly in the range of 550 to 650 J/g. Zurich hazard analysis (ZHA) provided assessment criteria for the severity of a runaway reaction on the four-level scale of the specific heat capacity, and Stoessel[80] made some modifications with respect to the high-risk group. DMSO is categorized as a high-risk material according to Stoessel's assessment criteria.

Babasaki et al.[75] calculated the maximum heat of DMSO decomposition to be approximately 2200 J/g (25 °C) according to the simple reaction scheme shown in Eq. 18.

$$\mathrm{DMSO} \rightarrow \mathrm{C} + \mathrm{S} + \mathrm{CH_4} + \mathrm{H_2O} \qquad (18)$$

As Eq. 18 is an ideal reaction scheme, and many substances on the right side of the equation have been found. Additionally, Eq. 18 suggests that the formation of S (0) leads to a large exothermic reaction, with a valence change in sulfur.

In a large vessel, neither mass transfer nor heat transfer is expected to be large enough to release the heat generated *in-situ*. Therefore, it is important to understand the thermal behavior of DMSO decomposition under adiabatic conditions from the viewpoint of safety in a chemical plant.

For safety purposes, a kinetic study is required for the control, mitigation and prevention of the thermal hazards during DMSO decomposition. The general principle of kinetic analysis under adiabatic conditions was discussed by Dammers et al..[132] followed by Townsend,[133,134] Morisaki[135,136] Kikuchi,[137] and Iizuka et al.[138] Chervin et al.[139] developed kinetic equations of autocatalytic decomposition of nitrobenzene derivatives. Comprehensive discussions were presented via the ICTAC Kinetics Project, 2000.[140]

According to Iizuka et al..[138] self-heating rates ($dT/d\theta$) are expressed by Eq.19 based on the hypotheses below.

i. Reactions occur under adiabatic conditions.
ii. The temperature of the reaction vessel increases in proportion to the conversion of the reactant.
iii. The specific heat and reaction heat remain constant in the temperature range where the exothermic reaction is observed.

$$\frac{dT}{d\theta} = k \cdot \left(\frac{T_f - T}{\Delta T}\right)^n \cdot {C_o}^{n-1} \cdot \Delta T \qquad (19)$$

where T is the temperature in an absolute scale; θ is the time; T_f is the final temperature; k is the rate constant; n is the order of the reaction; C_o is the initial concentration of the reactant; and ΔT is the adiabatic temperature rise corresponding to T_f - T_o, respectively.

The pseudo rate constant k' is expressed by Eq. 20 after certain formula induction. The general principle and the induction of mathematical expressions are shown in the Supplemental Information.

$$\ln k' = \ln\left(A \cdot {C_o}^{n-1}\right) - \frac{E}{RT} \qquad (20)$$

4.7.2 Evaluation of the self-heating rate plot under adiabatic conditions.

ARC is a well-designed and powerful tool for such investigations, as it provides pseudo-adiabatic conditions. ARC has two operation modes: i) heat, wait, and search

(HWS) mode and ii) isothermal aging mode. When using the HWS mode, it is easy to conduct the test within a certain period to obtain the thermal properties of an unknown substance. Therefore, many researchers have used the HWS mode to study DMSO decomposition.

In contrast, the isothermal aging mode provides the direct tracking of the exothermic process, including a relatively long induction period. Although it is difficult to estimate how long the test will take, the isothermal aging mode is suitable for obtaining direct information regarding the induction period. Calorimetric studies using the isothermal aging mode are demonstrated in the second half of this work.

4.7.3 Experimental section

Isothermal heating of DMSO was carried out using ARC with or without the addition of foreign impurities that could work as autocatalysts. In the case of acids, a small portion of acid was added to DMSO before starting the isothermal heating test. The headspace was filled with inert gas, and the temperature was set to 185 °C. To observe the effect of the environmental gas, air and carbon dioxide were introduced separately introduced into DMSO using a small tube as a bubbler, and the headspace of the bomb was carefully sealed with the same gas. Isothermal heating tests were conducted on these samples at 185 °C. The detailed ARC experimental conditions are described elsewhere.[15]

From a sequential data file consisting of (time, temperature), the absolute temperature (T) and reciprocal T ($1/T$) were calculated. To take the thermal capacity of the ARC bomb into account, the thermal inertia Φ was set to 2.08, where $\Delta T=\Delta T_{obs}\times\Phi$. On the other hand, the self-heating rate at t_n (m_{tn}) was obtained from the Eq.21.

$$m_{tn}=(T_{n+1}-T_{n-1})/(t_{n+1}-t_{n-1}). \qquad (21)$$

4.7.4 Results and discussions

A self-heating rate curve was obtained by plotting the natural logarithm of the self-heating rate (m_{tn}) against the reciprocal T ($1/T$), as shown in Figures 34-39A. For clarification, the scale of the X-axis was converted to °C, as shown in Figures 33-39B. When the self-heating rate ($dT/d\theta$) became larger than 0.02 °C/min in the induction period, the temperature and time were regarded as the initial decomposition temperature (T_0) and initial decomposition time (θo), respectively.

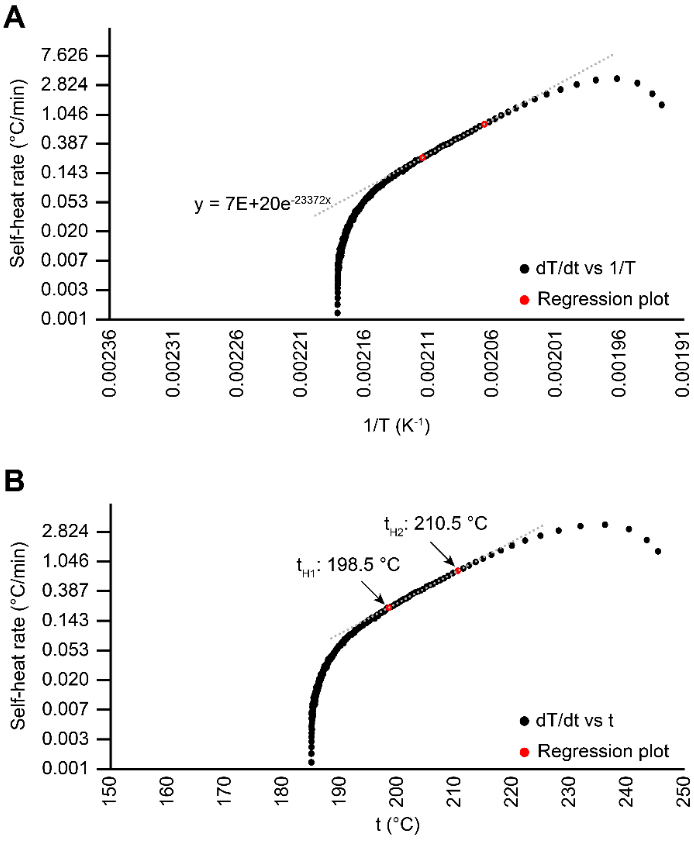


Figure 34. Self-heat rate plot 1 (Neat DMSO).

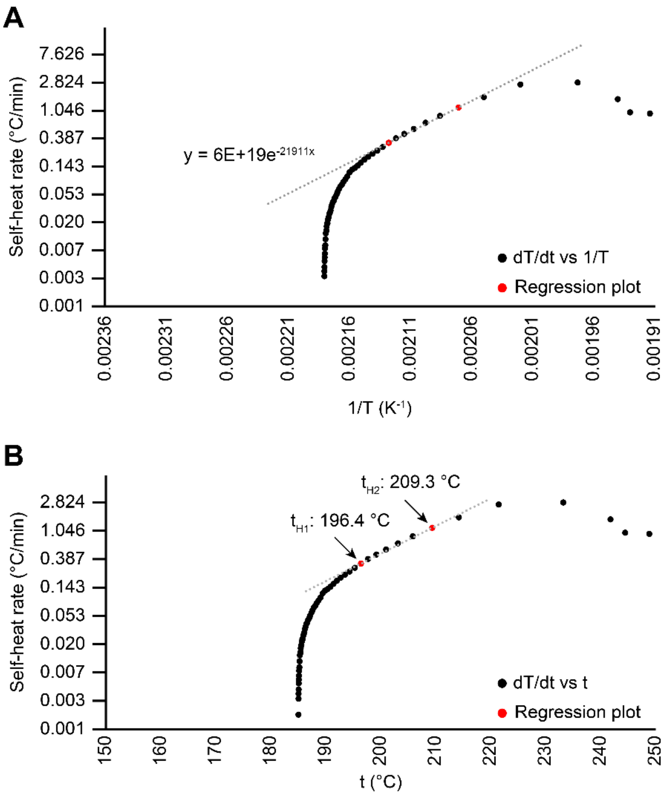


Figure 35 Self-heat rate plot 2 (Formic acid 2000 ppm)

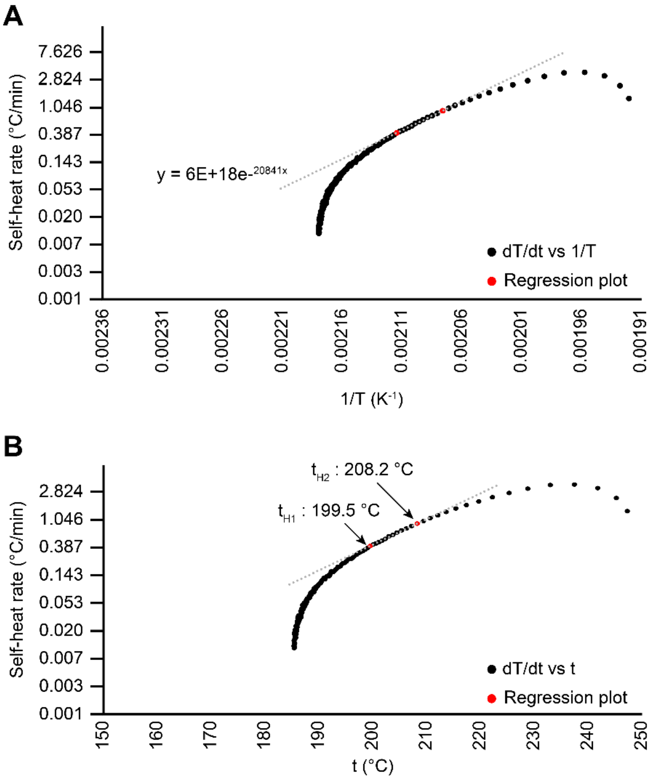


Figure 36. Self-heat rate plot 3 (Methanesulfonic acid 140 ppm).

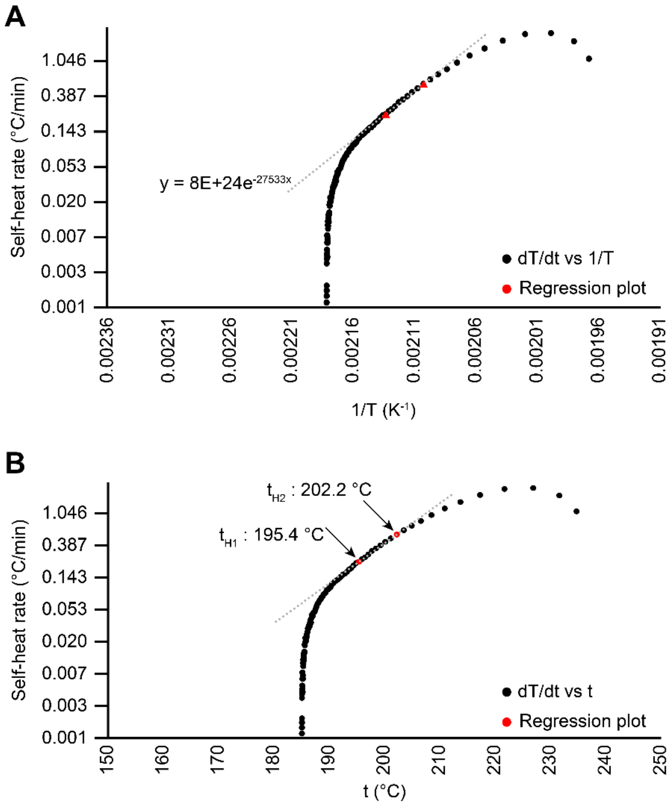


Figure 37. Self-heat rate plot 4 (Sulfuric acid 40 ppm).

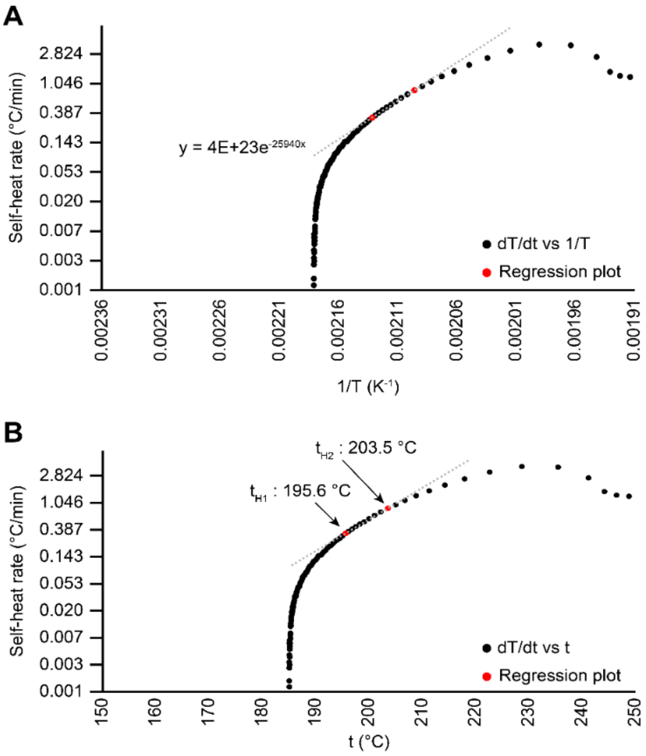


Figure 38. Self-heat rate plot 5 (CO_2 atmosphere).

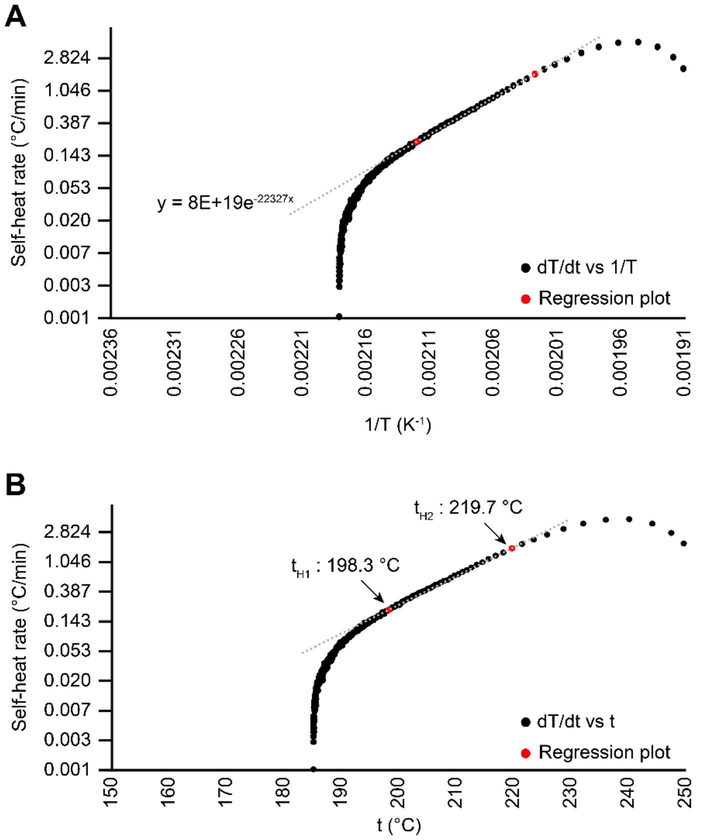


Figure 39. Self-heat rate plot 6 (Air atmosphere).

As seen in Plot B, all self-heating rate plots are bent at approximately 190 °C with a convex shape on the top. In the case of autocatalytic decomposition, it is known that the self-heating rate plot is bent in the early stage, unlike ordinary n-th ordered reactions. The self-heating rate plot is also reported to be affected by not only temperature but also by the thermal history test sample experienced. All entries herein showed a characteristic profile of the autocatalytic decomposition. Regression fitting was performed using a linear portion at a higher temperature range, as shown in Plot A. Kinetic data were obtained for various DMSOs with or without impurities using a model of n=1 in Eq. 21 and are summarized in Table 10.

Table 9. Summary of the kinetic data obtained for various DMSO samples.

Entry	Impurities	Initial temperature	Initial time	Largest self-heat rate	Activation energy
		T_0 (°C)	Θ_o (min)	$dT/d\theta$ (°C/min)	Ea (KJ/mole)
1	None (Neat DMSO)	185.6	11917	2.82 at 233.2 °C	182.2
2	Formic acid 2000 ppm	186.6	2714	3.51 at 236.2 °C	194.3
3	Methane Sulfonic acid 140 ppm	185.8	3252	3.69 at 237.4 °C	173.2
4	Sulfuric acid 40 ppm	185.7	5773	2.29 at 226.8 °C	228.9
5	CO_2 atmosphere	185.6	4840	3.93 at 228.7 °C	215.7
6	Air atmosphere	186.2	2325	4.52 at 240.2 °C	185.6

First of data analysis, the initiation temperature T_o does not have significant meaning here, as these tests were carried out in isothermal mode at 185 °C, and all T_o values are in a very small range. If we use ordinary HWS mode, then T_o may vary. In contrast, the initial decomposition time (θo, corresponding to the length of the induction period) varies widely depending on the impurities added.

The activation energy obtained for neat DMSO is 182 kJ/mol. Other entries containing impurities showed similar activation energies within a certain range, whereas the reported activation energy for neat DMSO varied more widely, according to Brandes and Smith.[70] Similarly, there was no big difference in the largest self-heating rate among the entries. Impurities largely shortened θo; however, they are supposed to have little influence on the main reaction. As a result of these findings, autocatalysts in DMSO decomposition, appear to work not in accelerating the main decomposition but in shortening the induction period.

One interesting observation documented by Koizumi,[119] was the retardation effect of polyphenols, generally used as an anti-aging substance for polymeric materials, on DMSO runaway decomposition. No neutralization to capture acids, but radical trapping is expected for a function of polyphenols. This means that DMSO runaway decomposition does not take place as long as polyphenols are active. By combining the chemical analyses of the decomposed materials described above, it is plausible to think that the main decomposition of DMSO undergoes *via* a radical path.

Regarding the question “What works as a decomposition promoter?”, it is assumed that both acids and radicals participate in DMSO decomposition. Acids are formed and accumulate gradually *in-situ*, and they do not contribute to accelerating the main decomposition. Such behaviors are unlikely to result in vigorous decomposition, although acids meet the general definition of autocatalyst. It is assumed that a handover from acid to radical is placed at the turning point, although the critical mechanism is still veiled.

Another interesting observation in the self-heating rate plot is that some exothermic events were observed after the completion of the main peak. Multiple exothermic events at later times were reported by Brandes and Smith,[70] and in the prior publications cited therein. The reason why we observed only one peak is probably because our cutoff timing was slightly earlier than the other authors.

This event is relatively small and isolated from the main exothermic peak, suggesting that the heat source of this peak is not the DMSO itself. Instead, this event is supposed to be from a higher-order reaction derived from the decomposed substances formed in the main decomposition. For example, the termination of radicals to create a sigma bond may generate an exotherm in the last portion of the decomposition. The other possibility is the polymerization of the monomer such as, ethylene and formaldehyde, which are also formed in the main decomposition.

4.7.5 Brief conclusion of this section

In this study, a kinetic study was carried out to observe the main decomposition of DMSO. The notable findings are described as follows:

i. Self-heat rate curves were drawn for various DMSO samples based on the isothermal heating test. All curves are bent at approximately 190 °C regardless of the presence of impurities.

ii. All DMSO samples, with or without impurities, showed similar activation energies and the largest self-heating rates, whereas the induction period was greatly shortened with a presence of impurities. It suggests that the autocatalyst in DMSO decomposition works not in accelerating the main decomposition, but in shortening the induction period.

iii. Some exothermic events are observed after completion of the main peak, suggesting that this event is from a higher-order reaction derived from the decomposed substances in the main decomposition.

5 Safe handling system of DMSO

5.1 Brief summary of conditions for autocatalytic decomposition of DMSO

By combining the knowledge gathered from prior studies with all the new findings accumulated up to the previous chapter, a safe handling system of DMSO can and should be considered for all chemical industries.

As mentioned in Chapter 3.2, there are many DMSO incompatible substances. When these incompatibles are mixed with DMSO, the thermal stability of the DMSO is reduced. Especially in the case of highly reactive incompatibles, such as perchloric acid[50] and phosphorus pentoxide,[141] a DMSO explosion can occur even at room temperature. Careless contact with such substances is a serious problem, however that should be treated as a matter of contact incident. In this dissertation, the focus is on only the mild incompatibles and the conditions that may lead to autocatalytic decomposition.

The difficulty in using DMSO in an industrial setting is due to the long induction periods during the autocatalytic decomposition, which make the abnormalities in temperature and/or pressure difficult to detect. To prevent undesired runaway decomposition situations, the following conditions are reviewed:

5.1.1 Temperature and time

DMSO should not be kept at high temperatures for a long period, as it increases the risk of runaway decomposition. In the case of neat DMSO, one of the manufacturers[6] documents that it rarely decomposed in air below 140 ° C, but that decomposition started near the boiling point 189 ° C.

When distilling the contaminated DMSO, it is recommended to use vacuum distillation to lower the heating temperature. The manufacturer issues a safety warning that heating should be stopped immediately if the internal temperature exceeds 160 ° C during distillation.[3]

5.1.2 Effects of impurities and atmosphere

Any solute that is dissolved in DMSO will reduce the thermal stability of DMSO to a greater or lesser extent. Even if the onset temperature does not show a noticeable change during the DSC ramp test, the induction period can be shortened in the isothermal heating test. The more impurities that are contained in the solution, the shorter the induction period becomes.

Oxygen and oxidants promote the oxidative decomposition of DMSO, and thus shorten the induction period. In the case of isothermal heating in an air atmosphere, it was reported that a very short induction period was observed.[2]

In the case of an incident at a sugar ester production plant, where generation of formic acid is suspected, an explosion took place during the evaporation at 160 ° C.[142]

It has been pointed out by many authors that hydrogen halides significantly lower the decomposition temperature in the presence of even just a small amount of contamination. Thus, neutralizing the acid to a neutral salt is recommended by the manufacturer to mitigate the DMSO decomposition. Br salt, however, is an exception, as it lowers the onset temperature significantly.

5.1.3 Blind spots that may be overlooked

There is a report that claims that unpurified DMSO that was stored in a drum at room temperature for a long period exploded when it was taken out of the drum and heated for the distillation process.[80]Thus, one should avoid storing DMSO in a contaminated state for a long period, even at room temperature.

5.2 Use of DMSO in industries

5.2.1 DMSO recovery and runaway decomposition

Using DMSO as a solvent, is nothing more than mixing impurities into DMSO, from a different point of view. Since DMSO is a relatively expensive solvent, it is not economically feasible to dispose it after a single use. When DMSO is used in an industrial setting, its proper use is as a solvent. It is like an artery that delivers blood to the body. But in addition to that primary purpose, it is necessary to consider the recovery and purification of the substance. This function in the previous analogy would be like the veins. It is important to build a safe recycling process for DMSO.

Autocatalytic decomposition becomes a problem when contaminated DMSO is heated for a long time, such as during evaporation and distillation. Maintaining a steady and continuous state is the key to keeping the operation stable during the chemical processes, that may operate continuously all day long. And in such situation, contaminated DMSO may have to be stored in a heated state for extended periods of time.

5.2.2 DMSO composition expected in the recovery process

DMSO recovered from industrial processes generally contains organic, as well as inorganic substrates. When used as a paint remover or spinning solvent, the recovered

DMSO often contains water molecules as well, which then often brings in acids and/or bases. In these situations, we need to consider that the recovered DMSO consists of a mixture of DMSO/water containing high molecular weight organic substances and inorganic ions.

5.2.3 Investigation of purification method

Some scientists have tried to remove water from a mixture of DMSO/water by using a membrane separation technique.,[143] Unfortunately, the membrane is weak against surface pollution, and it is not practical in terms of durability.

In the case where water content is low, a dehydrating material such as molecular sieves may be used. However, no methods other than distillation have been found to be a practical separation technique in obtaining high purity DMSO, when the water content is high.[144]

At least two distillations are required to remove multiple impurities, 1) non-volatiles and 2) water, from the recovered DMSO. The following two procedures should be consided. In both cases, the distillation/evaporation shall be carried out in a vacuum operation.

The first one is Plan A, in which water, having the lower boiling point, is distilled out first , and then the DMSO containing non-volatiles is transferred to the second distillation tower. DMSO with non-volatiles should be heated to collect pure DMSO from the top of the tower, while the non-volatiles are discharged periodically from the bottom.

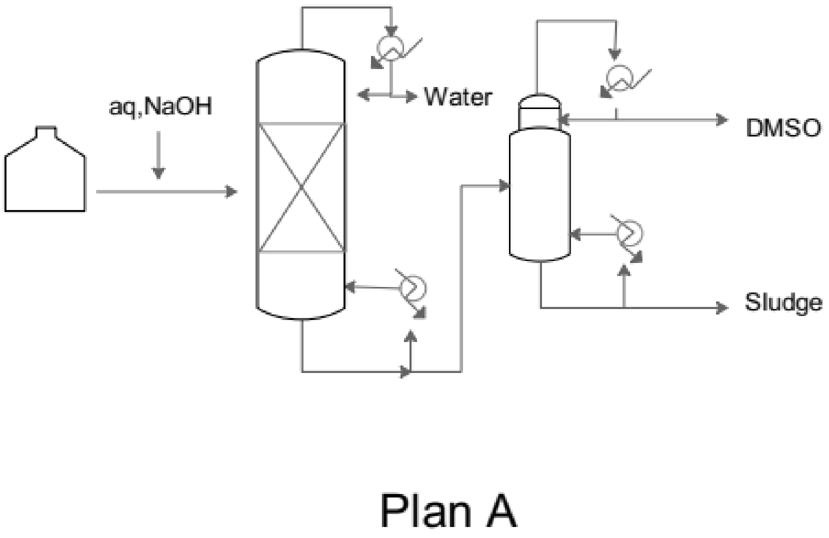


Figure 40. Distillation system “Plan A”

The other method is Plan B, in which water and DMSO are distilled out to cut off any non-volatile impurities first, followed by the DMSO/water , to obtain pure DMSO from the bottom of the tower.[3]

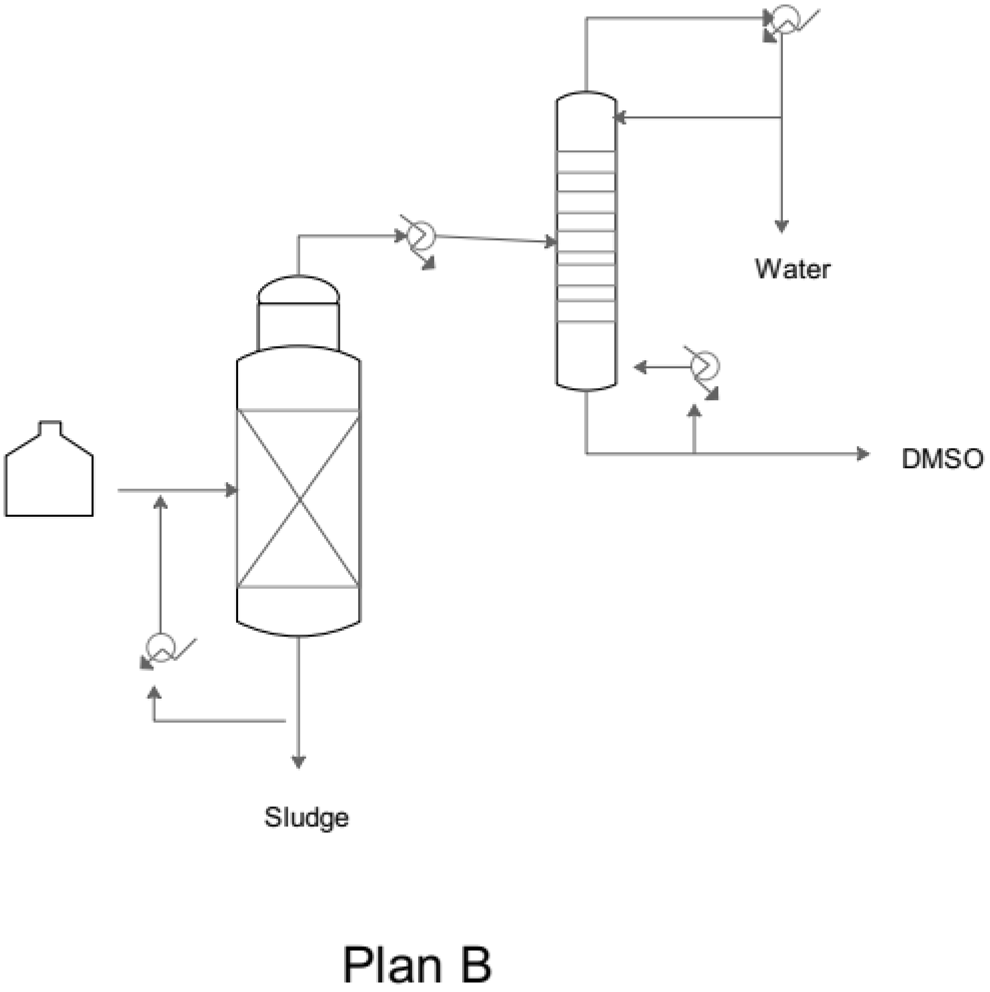


Figure 41. Distillation system “Plan B”

5.2.4 Comparison of the two distillation systems

Two distillation systems are compared as follows:

Plan A: Since only water is distilled out in the first tower, there is an advantage that the heating temperature of the first tower can be kept low. On the other hand, since DMSO containing non-volatiles is transferred to the second tower, the non-volatiles are concentrated at the bottom of the second tower. However, since DMSO is heated with concentrated non-volatiles for a long period of time, there is serious concerns about the

DMSO decomposition. This is an undesirable method when considering the risk of runaway.

Plan B: Since all volatile fractions are distilled out in the first tower, non-volatiles are cut off and discharged as a sludge. The risk of runaway decomposition of DMSO in the second tower can be reduced significantly compared to that of Plan A. On the other hand, it is predicted that it may be difficult to send the volatile fractions to the second tower in a vapor state. Assuming that a heat exchanger can be installed between the two towers to liquefy the vapor, it may be slightly disadvantageous in terms of energy consumption.

Based on the discussions in Chapter 5.1, Plan B should be adopted, as it has a much lower risk of runaway decomposition,

5.3 Process safety in chemical industries

Process safety in the chemical industry is reviewed, assuming a new DMSO distillation system is to be built.

5.3.1 Safety in chemical industries

Since the beginning of time, human life has existed with risks, accidents, and disasters. Avoiding accidents and protecting oneself is of great concern to most individuals. However, this is owed much to one’s experience and knowledge, rather than the responsibility of a certain group. It may be said that safety is a personal issue.

During the periods of rapid industrialization after the Industrial Revolution, capital accumulation and the separation of workers and capitalists have progressed. At the same time, the damage from accidents has increased, and the importance of accident prevention has been recognized.[141] Much time has passed, and it is time for current industries to take responsibilities along with all relationships with their stake holders. Industrial safety should be the bottom-line goal of all activities.

Chemical industries have some unique characteristics when compared with other industrial fields.[145] The first being that chemical industries use large amounts of chemical substances, such as high-pressure gases, petrochemicals, toxic chemicals and even explosive materials, which may be harmful to the human body and the environment. Secondly, various chemical reactions that are carried out in the production every day, potentially have a risk to run-away if not properly handled. Unfortunately, there is a concern among safety personnel that only the involved department knows in detail what is going on in the reaction vessel. These negative aspects can be the downfall of the chemical industries.

In many chemical industries including food processing, pharmaceuticals, textiles, etc., manufacturing is usually carried out using equipment in a system to maximize economic efficiencies, taking advantage of things such as scale merit, and continuous production. This is different from other industries that deal with machinery, electrical and electronic equipment. They are classified as processing/assembly production in terms of production system, and their management methods, including safety issue, are slightly different from the ones in chemical industries. Of course, there are parts even in the chemical industry where the competence of workers and the organizational structure affect safety, not only in a manufacturing capacity but also on the equipment utilized and the plant design.[146,147]

In the current business communities, it is a common sense to place a set of important things represented by the phrase “Environment, Health and Safety” on the bottom line of all corporate activities. And indeed, various efforts are now undertaken to meet the tide directing toward sustainable world. Japan Chemical Industry Association (JCIA) declares 9 principles regarding the Environment, Health and Safety as follows.[148]

i. Safeguard the environment, health and safety in both domestic and overseas operationsthrough strong leadership. by management.

ii. Strive to continually improve environmental, health and safety performance and the security of facilities, processes and technologies throughout the entire chemical lifecycle, from development to disposal, and inform society of the results. of such efforts.

iii. Further reduce consumption of resources and energy, and strive to reduce, reuse and recycle wastes.

iv. Protect the environment and people's health and safety, by driving continual improvement in chemical product safety and stewardship throughout the supply chain.

v. Strengthen chemicals management systems by participating in the development and implementation of lifecycle-oriented, science-based, and risk-based sound chemical management legislation and best practice.

vi. Influence business partners to promote the safe management of chemicals within their own operations.

vii. Strive to engage in dialogue with local authorities and communities by heeding their concerns regarding the effects of our products and business activities on the environment, health and safety. Provide them with the necessary information to understand properly.

viii. Further expand dialogue locally, nationally and globally in order to better meet the expectations of stakeholders regarding our efforts with respect to the environment, health and safety.

ix. Contribute to the sustainable development of society by developing and providing innovative technologies and other solutions.

Elucidation of the decomposition mechanism and runaway behavior of DMSO, which is a main body of this study, is an example where the company in charge can show their best efforts to meet the compliance. Continuous efforts to keep or even improve the facilities in the chemical plant are indispensable for establishing safety standards

5.3.2 Process Safety in Chemical Industries

Kidam and Hurme[149,150] analyzed chemical process incidents twice using the Japanese Failure Knowledge Database. They found in most cases the primary cause was technical. Incidents occurred due to failure of auxiliary systems, design error, chemical reactivity and incompatibility, operating beyond the equipment limits, and underestimating thermal expansion phenomena. It is no surprise that piping was the largest contributors, but in the end seeking for root causes it turned out to be the lack of knowledge, not learning from previous incidents, or just human error. Their reports are slightly outdated, but we can still learn from them.

5.3.3 Multi-layered structure of safety

In safety engineering, there is a personal proposal called “Chemical Safety Engineering Research” in the field of pursuing and improving safety through prevention and mitigation of incidents and disasters in chemical plants.[151] Chemical plants herein perform a wide range of functions such as reaction, separation, purification, storage, transportation and disposal of chemical substances.

In the discussion with respect to “Chemical Safety Engineering Research”, a three-level structure is acknowledged as shown in Figure 42. As can be seen from the fact that representative textbooks in safety engineering are divided into three volumes; material safety, process safety, and safety management,[152- 154] it is generally accepted to address that safety issues are lying in chemical industries with a three-story structure.

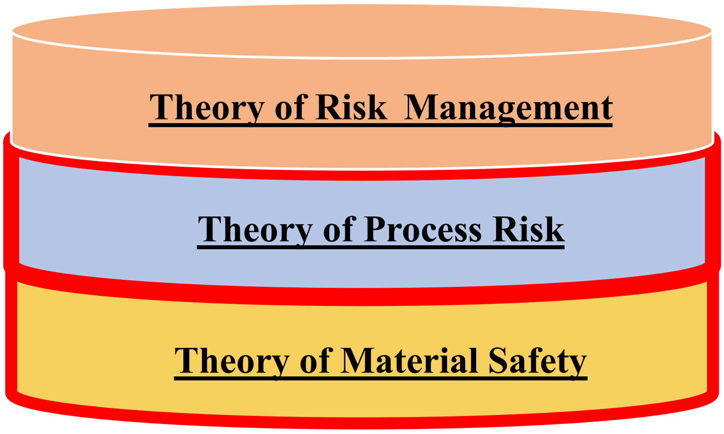


Figure 42 Three-story structure of Chemical Safety Engineering Research

The theory of material safety is found at the lowest level, since each substance handled has different chemical and physical properties. It makes sense that the reaction conditions and unit operations related to the theory of process risk are positioned at the medium layer. To build-up safety theory, it is considered normal to position the theory of risk management at the top layer.

5.3.4 Multiple protective measures

In the past, there was a time when it was enough for process design to meet compliance with various legal regulations. However, due to the frequent occurrences of chemical plant incidents in the United States in the 1980s, the mainstream trend in ensuring safety turned into the continuous responsibility of each individual company's followed by appropriate risk reduction measures.

In the event of system or device failure due to a mis-operation or malfunction, it is required to keep the device or system under control any time. This is called a “fail safe system”, and this idea came about from the premise that devices and systems will “always fail”.

A chemical plant has a large number of devices and parts, and it is possible that just one failure can affect other areas and lead the entire plant to be affected by the failure. Therefore, it is recommended to place multiple protection layers, using both hardware and software measures where risks are expected.

Another layer structure that involves ensuring the safety of chemical plants, was proposed by the Center for Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers (AIChE). Safeguards or barriers like an “onion” are required for risk reduction.[155]

Barriers come in predominantly two forms; one is a preventive (or proactive) type, and the other is a protective (or reactive) one. The former, for example, would be walls that are continuously present in the same place and thus reduce the effects of an emergency release. The latter are the barriers that are triggered by process variable when an abnormal situation happens, and which will actively bring a process back into a safe state. Due to such differences, each layer should be independent as shown in Figure 43.

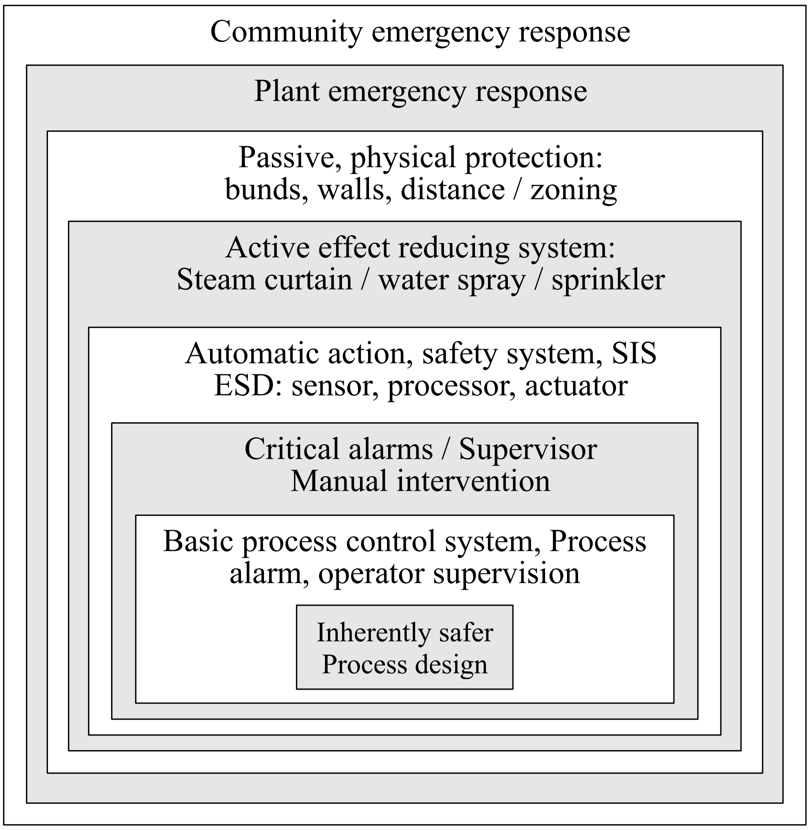


Figure 43. Independent protection layer- “onion”

5.4 Process development and incorporation of safety measures.

5.4.1 Stage-Gate of process development and safety measures

It is difficult for a company to survive in a competitive environment unless otherwise striving for metabolism. Thus, it is important to incorporate new product lines and processes continuously. Innovation is the lifeline for a company.

The process of reflecting the results of R&D in production is often considered to be a risk. It is possible in the projective work to develop new products or processes, which work well at the laboratory scale, but may not perform satisfactory as expected in the industrial scale. The other problem ismatching with customers' needs or requirements. It is essential to confirm the propriety repeatedly in the project management. It has been a central proposition of the Management of Technology (MOT) to determine how tobalance technology maturity with customer needs.

Stage-Gate® method was established by Cooper in the mid-1980s to install gates between every stage of development to evaluate whether interim goals are being met.[156] As this management method matches the R&D field, many companies have adopted this method with some arrangements in their project management. Cooper himself stated "Many leading firms have built in dozens of new best practices, so that today's stage-and-gate processes are a far from the original model."[157]

Thus, there are many derived methods, but the basic concept is to make a "barrier in the water flow" and perform reviews and make decisions as shown in the Figure 44.

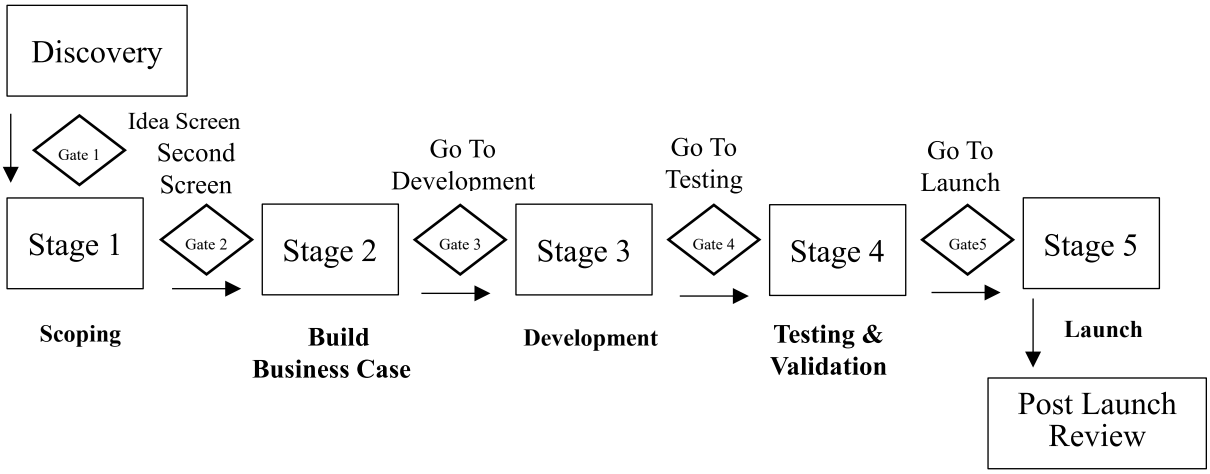


Figure 44. Stage-Gate® Process in R&D.

Milestones are set at each gate, and decisions shall be made after certain review steps. Safety issues shall be included and reviewed, just as other technical and marketing issues.

5.4.2 Risk management of the chemical plant handling energetic materials

For the plant risk management (RA), risk assessment shall be first carried out according to the general procedure, and countermeasures are devised based on the results of RA. Risk assessment should basically be carried out according to the following procedure.

i. Setting the target of risk assessment
ii. Collecting information on equipment characteristics, social conditions, weather conditions, etc.
iii. Hazard identification and selection of initial situation
iv. Identification of hazards
v. Estimating the frequency of hazards
vi. Damage prediction by impact analysis of hazard
vii. Risk evaluation
viii. Risk assessment

5.4.3 Proposal to incorporate safety measures

In the past cases, it has been pointed out that safety devices installed in already completed plants sometimes no longer function sufficiently. Safety devices must be considered as fundamental equipment, not just additional equipment, therefore it should be built-in the plant.

Since a chemical plant has a large number of devices and parts, it is not easy to sufficiently cover potential problems once production is started, no matter how much inspection and maintenance is performed. If remodeling work is required after the start of operation, it will be very difficult to carry out the work, Not only because of cost and time, but also because of the existing equipment and infrastructure. It is not as easy as constructing in a vacant space.

US National Security Council (NSC) showed a guideline that it is important to identify and evaluate the hazards of the plant as much as possible during the design stage, to reduce risks which lead to ensuring plant safety after the start of operation[158]. This is an idea so-called "Safety through design" as shown in Figure 45. Ease of achieving safety will be reduced by advancing the stage. On the contrary, cost to achieve safety will be increased *vice versa*. In the current chemical industries, the policy that ensuring plant safety should be made-up through design is becoming widespread.

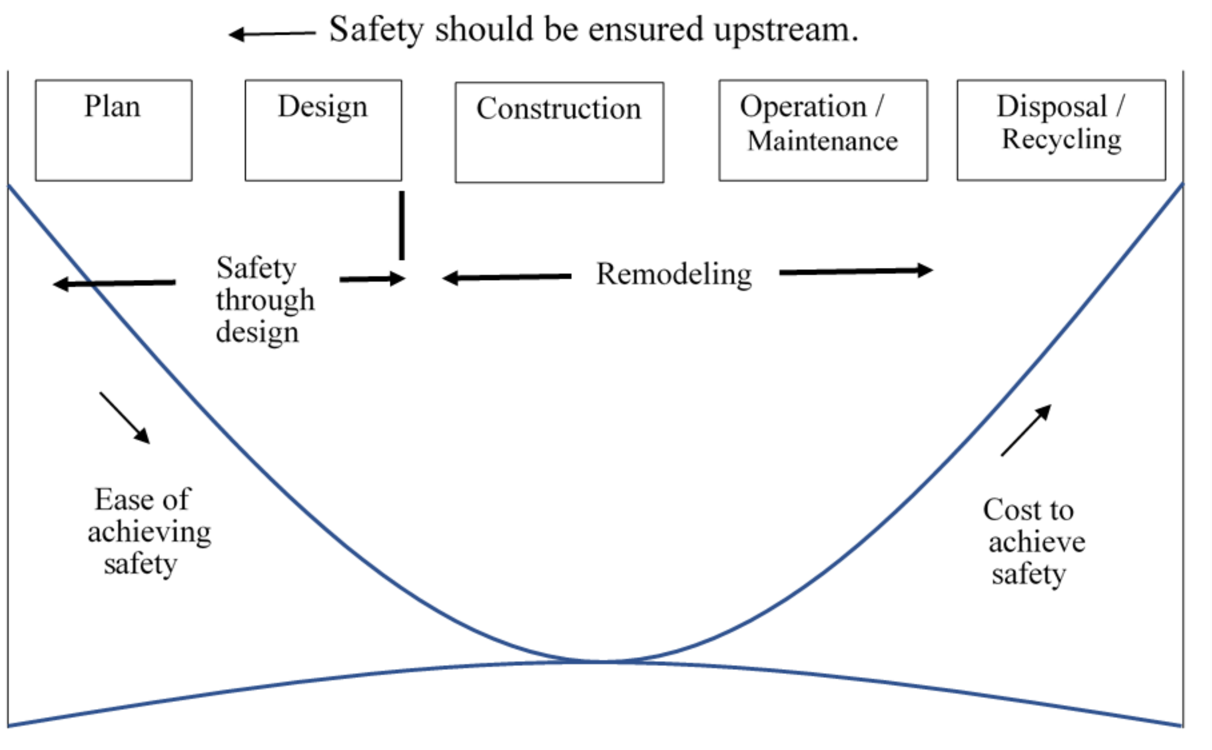


Figure 45. A model of "Safety thorough design" by NSC.

Actual company management is not exactly what the theory suggests. It is often the case that production processes will need to be modified from a business perspective at any stage. It should be notedthat safety assumptions may be changed, or risks may increase due to process modifications, such as increasing capacity, adding more product lines, energy saving and labor saving. Even if it is an improvement necessary for corporate management, it can be detrimental to the safety margin, from the viewpoint of safety.

In the stage-gate process, safety reviews should not be thought of as “once and done”. Instead, safety issues should be reviewed at each gate. The importance of change management is emphasized in safety engineering. The author would propose that the importance of change management should also be applied to the review in the stage gate.

6 Conclusions of this dissertation

6.1 Achievement

The first achievement of this dissertation is the elucidation of the mechanism of DMSO autocatalytic decomposition. The autocatalytic nature of DMSO is cumbersome to handle in industries, as undesired vigorous decomposition can suddenly begin after a long induction period. Until this study, while pointing out the difficulty of autocatalytic decomposition, it was not clear what the autocatalytic substances were. It is shown that acids generated *in-situ* work as autocatalysts of DMSO decomposition. However, the main decomposition proceeds *via* a radical path, and not *via* an acidic path. Such a take-over process of decomposition has not been reported so far. The findings regarding the autocatalytic decomposition of DMSO shall make a contribution both academically and industrially.

The second achievement of this study is the proposal to have a safe handling system for DMSO. Conditions to induce autocatalytic decomposition were summarized, and the importance of purification was described. Two distillation schemes were considered and compared. The Stage-Gate® method in process development is described, and it is proposed that the importance of change management should also be applied to the review in the Stage-Gate®. This proposal may be a sour story for the company as it may be seen lightly in a hurry.

The last and partially hidden achievement is to show several examples of the advanced analytical techniques applied in the field of material safety. However, the analysis of decomposed products itself is a classic research method of runaway reaction. Various analytical techniques were introduced and combined to figure out the complicated phenomena in this study. However, the critical point that had been overlooked in past studies is the careful observation of the sample or phenomena. Careful observation made a difference in this study.

6.2 On-going work

Since this work is considered to have achieved certain results, this dissertation is going to be a milestone. However, there are some unaddressed issues in terms of material safety in DMSO as follows. The author will continue to work to achieve these goals.

6.2.1 Capturing and analysis of radicals generated *in-situ*.

In our investigations described here, it is elucidated that the radical path is the major player in the main decomposition of DMSO. We have a desire to capture the radical generated *in-situ* to correctly identify the radical species. No such attempts have been reported however, perhaps due to the safety concerns dealing with DMSO under runaway.

6.2.2 Detail take-over mechanism

It is clear that the promoter of DMSO decomposition is taken over from acid to radical, however the mechanism details are not sufficiently clear. Quantum calculations would be a powerful tool to solve this problem.

6.2.3 Construction of the overall view of DMSO decomposition.

Many authors have proposed elementary reactions of DMSO decomposition Most of which look rational at least in part. However, a sufficient overall view has not been drawn for DMSO decomposition. Construction of the overall view is the goal of this issue

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8. Publications

This dissertation is based on the following papers:

8.1 Journal papers

1) Deguchi, Y.; Kono, M.; Koizumi, Y.; Izato, Y.; Miyake, A. Study on Autocatalytic Decomposition of Dimethyl Sulfoxide (DMSO). Org. Process Res. Dev. 2020, 24, 1614-1620.
2) Deguchi, Y.; Kono, M.; Koizumi, Y.; Watanabe, Y.; Fujita, M.; Izato, Y.; Miyake, A. Study on Autocatalytic Decomposition of Dimethyl Sulfoxide (DMSO) II. Analysis of intermediate substances obtained in the induction period and investigations regarding formic acid. Org. Process Res. Dev. under review.
3) Deguchi, Y.; Kono, M.; Koizumi, Y.; Watanabe, Y.; Fujita, M.;Izato, Y.; Miyake, A. Study on Autocatalytic Decomposition of Dimethyl Sulfoxide (DMSO) III. Investigations with Respect to Main Decomposition. Org. Process Res. Dev. under review.

8.2 Conference papers

1) Deguchi, Y.; Iizuka, Y.; Izato, Y.; Miyake, A. Decomposition of DMSO in nitrogen atmosphere and analyses of resulting substances. Proceedings of the 12th European Symposium on Thermal Analysis and Calorimetry. Brasov, Romania. August 29, 2018.
2) Deguchi, Y.; Kono, M.; Koizumi, Y.; Izato, Y.; Miyake, A. Study on autocatalytical decomposition of dimethyl sulfoxide (DMSO). Proceedings of 84th Annual Meeting of The Society of Chemical Engineers, Japan. Tokyo.

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3) Deguchi, Y.; Kono, M.; Koizumi, Y.; Izato, Y.; Miyake, A. Autocatalytic Decomposition of Dimethyl Sulfoxide (DMSO). Proceedings of The 4th International Symposium on Process Chemistry. Kyoto. July 26, 2019.
4) Deguchi, Y.; Kono, M.; Koizumi, Y.; Izato, Y.; Miyake, A. Study on autocatalytic decomposition mechanism of dimethyl sulfoxide (DMSO). Proceedings of International Conference of Loss Prevention, Process Safety, and Thermal Analysis in Chemical and Coal Industries. Yunlin, Taiwan. November 26, 2019.
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Yoshikuni Deguchi