# Dibenzothiophene-S-oxides-an Overview

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# Dibenzothiophene-$S$-oxides – an Overview

Thies THIEMANN, Kazuya ARIMA, Shuntaro MATAKA

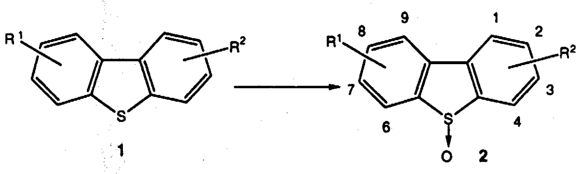
In this review on the class of dibenzothiophene-$S$-oxides the preparation, the structural and physical properties as well as the reactivity of these molecules are presented. Moreover, their importance as intermediates into the microbial transformation of environmentally harmful dibenzothiophenes is highlighted. Possible technical applications are also discussed.

## Introduction

This overview is the first of a series of three reviews on the preparation, the physical properties and the chemical reactivity of benzothiophene-$S$-oxides, dibenzothiophene-$S$-oxides and thiophene-$S$-oxides.

## Preparation

The sulfur atom in dibenzothiophenes (DBTOs) is much less prone to oxidation than that in normal organic aryl sulfides. Thus, perbenzoic acid oxidizes diphenyl sulfide 100 times faster than dibenzothiophene.[1] Nevertheless, a number of preparations of DBTOs via the oxidation of the corresponding dibenzothiophene have been devised.



| | | | | |
|---|---|---|---|---|
| $Cl_2$, $CCl_4$; $H_2O$ | DBT | | | Fries, Vogt, 1911[2a] |
| ... | DBT | 77% | | Brown, Christiansen 1948[2b] |
| $H_2O_2$, HOAc | DBT | 71% | | Gilman, Esmay 1952[26] |
| $H_2O_2$, $TiCl_3$ | DBT | 99%$^a$ | | Oae 1981[10] |
| $m$-CPBA | | 93%$^b$ | (2d, 0°C) | Hori 1974[5] |
| m-CPBA | DBT | 91% | (4h, -20°C) | Arima 1999/2000[6] |
| $m$-CPBA | 3,7-Dibromo-DBT | 84% | (2h, rt) | Arima 1999/2000[6] |
| $m$-CPBA/$BF_3$ | 3,7-Dibromo-DBT | 92% | (2h, -20°C) | Arima 1999/2000[6] |
| $m$-CPBA/$BF_3$ | 4,6-Dimethyl-DBT | 92% | (2h, -20°C) | Arima 1999/2000[6] |
| m-CPBA | 4-Iodo-DBT | 86% | (2h, rt) | Arima 1999/2000[6] |
| $Bu_4NIO_4$/TPPFe(III)Cl | DBT | 84% | | Takata, Ando, 1983[16] |
| $PhI(OAc)_2$ | DBT | 90% | | Castrillon 1982[12a] |
| Urea/$H_2O_2$ | DBT | 93%$^c$/96%$^d$ | ($^c$4h/$^d$2h) | Balicki 1992[13] |
| $NaBrO_3$/<br>$(NH_4)_2Ce(NO_3)_6$ (cat.) | DBT | 95% | (6h, rt) | Ho 1979[14] |
| $NaClO_2$, $Mn(acac)_3$,<br>moist alumina, acetone | DBT | 79% | (90 min, rt) | Hirano, Clarke,<br>Morimoto 1996[15] |

$^a$crude yield; $^b$isolated yield; $^c$MeOH; $^d$$CH_3CN$

Scheme 1 and Table 1. *Preparation of DBTO from DBT by Oxidation*

Halogenation, *i.e.* chlorination or bromination of dibenzothiophenes in $CCl_4$ with subsequent aqueous work-up yield dibenzothiophene-$S$-oxides in high yields.[2,3] Oxidative chlorination has also been reported for dibenzothiophene-$S$-oxide as a slurry in water.[4] At 70°C the major product was the sulfone, however. Nevertheless, this method can be seen as an interesting alternative to the oxidation with $m$-CPBA,[5] especially for compounds with easily oxidizable functional groups. The use of $BF_3$ as a Lewis acid allows the oxidation reaction to be run at lower temperatures than with $m$-CPBA alone.[6] Here, it can be expected on the one hand that the Lewis acid activates the peracid, on the other hand that it protects the sulfur of DBTO by complexation[9] to the oxygen against further oxidation to $DBTO_2$. This procedure has been used advantageously in preparing thiophene-$S$-oxides.[10] In the case of the DTBOs, however, the yields of both variants are comparable. Halogenated, e.g. brominated or iodinated, dibenzothiophenes can be oxidized under the same conditions.[6] Here the use of $BF_3 \cdot Et_2O$ as Lewis acid catalyst allows for better yields of the DBTO derivatives. Dibenzothiophene-$S$-oxide itself has also been prepared from dibenzothiophene by oxidation with $H_2O_2$ in the presence of $TiCl_3$ as a Lewis acid catalyst[11] and by iodosylbenzene diacetate.[12] A further preparation of interest is the oxygen transfer to the sulfur of DBT with 5.10,15,20-tetraphenylporphinato iron (III) chloride (TPPFe(III)Cl) as catalyst and $Bu^nNIO_4$ as the oxidant;[16] this way DBTO can be prepared in good yield. To this end, Mansuy et al.[17] have developed a catalytic system that uses oxygen directly, i.e., a P-450 model system. Mn(TPP)Cl is the catalyst, where 1-methylimidazole is used as a cocatalyst. The reaction is run in an acidified (acetic acid) solvent mixture of acetonitrile and dichloromethane, and zinc is used as the electron donor in the catalytic cycle. Yields, however, are only moderate.[17]

Other methods of oxidation involve sodium

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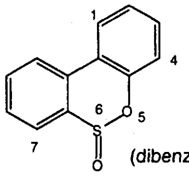
metaperiodate in basic aqueous DMF, a bromine complex of Troeger's base,[19] and $NO_2$ (0.3 mol%) with $O_2$ as a co-oxidant,[20] a sulfonic peracid prepared *in situ* from *p*-toluenesulfonylimidazole and $H_2O_2$ in the presence of aq. NaOH (yield of DBTO 8%),[21] and cesium fluoroxysulfate ($CsSO_4F$, $CH_3CN$, rt, 1h, Y. 35%),[22] but these methods are not always easy to handle and often tend to be non-reproducible. More exotic methods include the oxidation with $XeF_2$ in $CH_2Cl_2$ or acetonitrile in the presence of HF, $BF_3$ or $C_6F_5SH$.

The kinetics of the oxidation of dibenzothiophene to the corresponding *S*-oxide have been studied[24] and a mechanism has been forwarded.[24b] Thus, the chlorination in aq. acetic acid follows a regular second-order kinetics, first order in Cl and in DBTO.[24a] Neither the production of HCl nor the presence of LiCl affects the rate constant. NaOAc shows a very strong accelerating effect.[24a] Oxidation with iodosylbenzene diacetate is acid catalysed, but zero-order with respect to the oxidant.[24b] Kinetic data is also available for the oxidation of DBT with $MoO_5$·HMPT.[25] A measurement of the kinetic constant k with DBT at [0.1M], $MoO_5$·HMPT at [0.005M] in dichloroethane at 40°C gives a value of 0.042 $M^{-1}s^{-1}$. For comparison, the value for the oxidation of diphenylsulfide is with 34 $M^{-1}s^{-1}$ almost by a factor of 1000 larger under the same conditions.[25]



3 (dibenz[*c*,*e*]oxathiin-6-oxide)

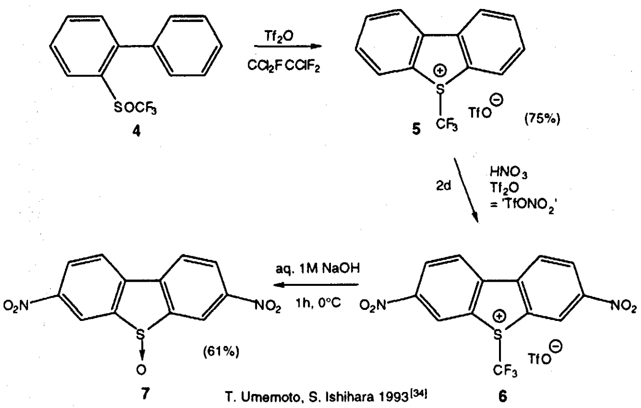
Figure 1

Interestingly oxidations of dibenzothiophenes with peracetic acid ($H_2O_2$/HOAc),[trifluoroperacetic acid ($H_2O_2/CF_3COOH$ [TFA]),[7] peroxymaleic acid (maleic anhydride/90% $H_2O_2$).[26] air in the presence of a ruthenium catalyst on alumina (100°C/12h)[8] all lead to the corresponding dibenzothiophene-*S*,*S*-dioxides, although it is possible with very careful control of the reaction conditions to prepare DBTO by reaction of DBT with $H_2O_2$/HOAc.[27]

Photooxygenation of arylsulfides is known.[28] DBTO is formed when DBT is photoirradiated in the UV range in the presence of oxygen.[29] While the method cannot be used preparatively, as DBTO itself is not photostable (Jenks et al. have noted that DBTO photodeoxygenates even at 77K at 1μM concentration)[32], this has been forwarded as the basis of a desulfurization process for light oil, where DBT is one of the sulfur-containing contaminants.[30,31] The process consists of a liquid liquid extraction of DBT from the light oil to a water-soluble polar solvent, in which under these conditions (i.e., in the presence of oxygen and water) DBT is decomposed photochemically via DBTO to DBT-dioxide, dibenz[*c*,*e*]1,2]oxathiin-6-oxide **3** (Figure 1) and aromatic sulfinates and sulfonates.[30] It has also been reported that the photoirradiation of a charge transfer complex of dibenzothiophene and tetranitromethane yields DBTO[33].

Dibenzothiophene-*S*-oxide has been found to be one of the products in the metabolic oxidation of dibenzothiophene by Pseudomonads isolated from crude oil, further products being 3-hydroxy-2-formylbenzothiophene and 3-methylbenzothiophene carboxylic acid (see the subpart on the environmental aspect of DBTO [see also ref. 64]).

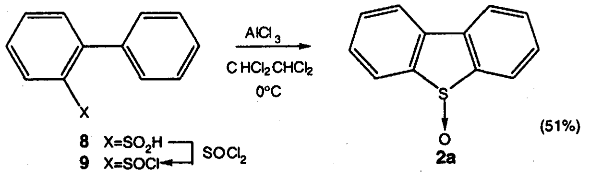
One preparative method that does not involve the direct oxidation of DBTO-derivatives, is the formation of **5** from 2-[(trifluoromethyl)sulfinyl]biphenyl (**4**), its nitration to **6** and the subsequent base catalysed hydrolysis of **6** to the corresponding DBTO **7** (Scheme 2).[34] In order to appreciate this method better, it must be stressed that very often suitably substituted DBTs, needed as starting material for the oxidation reactions to the DBTOs, are commercially not available and are very frequently prepared by ring closure reaction from the thio-substituted biphenyls.



T. Umemoto, S. Ishihara 1993[34]

Scheme 2 *DBTOs by base catalysed hydrolysis of dibenzothiophenium salts*

A second, related but earlier method based on the ring closure of the central five-membered heterocyclic system starts from 2-diphenylsulfinyl acid **8**, which is transformed to the corresponding sulfinyl chloride **9** (thionyl chloride). The sulfinyl chloride is subsequently ring-closed by Friedel Crafts reaction (tetrachloroethane, 0°C, 24h) to give DBTO in 51% yield (Scheme 3).[35]



W. Davies et al.[35]

Scheme 3 *DBTO by Friedel Crafts reaction*

## Structural and Physical Properties

An X-ray crystal structural analysis performed on DBTO by Horak et al.[36] shows that the thienyl-oxide ring deviates from planarity, where the sulfur atom protrudes by 0.05 Å from the plane defined by the four carbon atoms of the heterocyclic ring. The oxygen of the sulfoxy moiety comes to lie on the other side of that plane. Angles $\alpha$ and $\beta$ associated with this deviation from planarity are given in Figure 2. The structural features show great similarities with the geometry obtained for the parent thiophene-$S$-oxide from MNDO calculations.[36,37] For comparison these results are presented in Figure 2 along with data obtained from an X-ray structural analysis of 2,5-diphenylthiophene-$S$-oxide by D. Mansuy et al.[38]

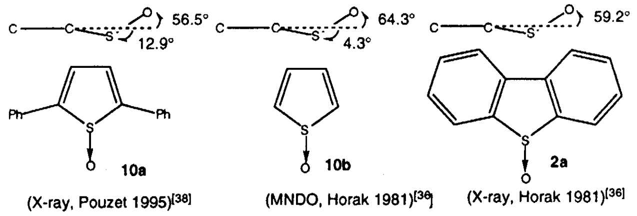


Figure 2 *Structural parameters of DBTO and thiophene-S-monoxides*

The C-S bond in DBTO with 1.790 Å[39] is significantly longer than the C-S bond in DBT (1.740 Å). This leads to a more pronounced bond alternation throughout DBTO. One indicative parameter for the aromaticity of a molecule is the $A$ value introduced by Julg and Francois,[40a] which quantifies the bond alternation in conjugated systems. In table 2 are presented the $A$-values of DBTO, DBT and fluorene as calculated by Horak et al.[36] on the basis of their X-ray crystal structure of DBTO and the X-ray structures of DBT (Trotter)[40b] and fluorene (Iball)[40c]. That the oxygen ligand on sulfur is not in the plane defined by the four C-atoms of the heterocyclic system would also indicate that the (remaining) lone electron pair on sulfur has a decreased overlap with the $p_z$ orbital of the two neighboring carbon atoms as compared to the overlap of the lone electron pair in the $p_z$ orbital of sulfur in the corresponding thiophene. This would explain, at least in part, the decreased aromaticity of DBTO. It is known, however, that the non-areno anellated thiophene-$S$-oxides suffer inversion at sulfur at elevated temperatures. The transition state of this inversion process has been calculated to exhibit a close to planar geometry. In what way the planar structure contributes to the aromaticity of the system is still a matter of discussion. Nevertheless, it must also be noted that the barrier of inversion of benzo[*b*]thiophene-$S$-oxide or DBTO has been calculated to be much higher than that of the unsubstituted thiophene-$S$-oxide (i.e., DBTO 32.3 kcal/mol; benzo[*b*]thiophene-$S$-oxide 23.9 kcal/mol; thiophene-$S$-oxide 11.2 kcal/mol).[39] This is attributed to the fact that, while the planar structure is stabilized by aromatisation, the stabilisation energy to aromatisation would taper off with the benzannulation.[39]

*A* indices according to Julg[40a]

| | 5-membered core | entire structure |
|---|---|---|
| Dibenzothiophene-*S*-oxide | 0.75 | 0.97 |
| Dibenzothiophene | 0.97 | 0.96 |
| Fluorene | 0.87 | 0.92 |

calculated according to: $A = 1 - (225/n)\Sigma_{rs}(1-(d_{rs}/d_{mean}))^2$
where $n$ = number of bonds; $d_{rs}$ = individual [averaged] CC bond lengths;
$d_{mean}$ = averaged CC bond length of all CC bonds of the structure

taken from Horak et al. 1981[36]

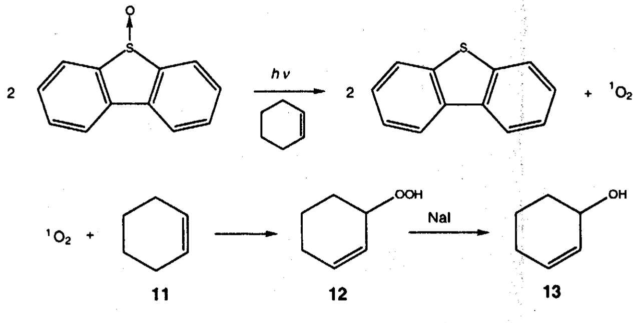
Table 2

Spectroscopically dibenzothiophene-$S$-oxide has been full characterized.[40]

## Reactivity

a.) Reduction/Deoxygenation: It has been shown that DBTO reduces electrochemically at a potential of about 0.6V more positive than that needed for the reduction of diphenyl sulfoxide under the same conditions.[42] Dibenzothiophene-$S$-oxide can be reduced smoothly to dibenzothiophene by sodium bis(2-methoxyethoxy)aluminum hydride (Red-al$^R$),[43] but also with $NaBH_4$ in a mixture of benzene and ethanol at rt, when *meso*-tetraphenylporphinato iron(III) (TPPFe(III)Cl) is employed.[44] In its presence, BNAH (1-benzyl-1,4-dihydronictoinamide) also acts as a reductant, but the reaction conditions are more drastic (80°C, 2-4h) for the conversion of DBTO to DBT. Dibenzothiophene-$S$-oxides are also reduced by $H_2$ over $CoO\text{-}MoO_3/Al_2O_3$ at 10 atm and 70°C.[45]

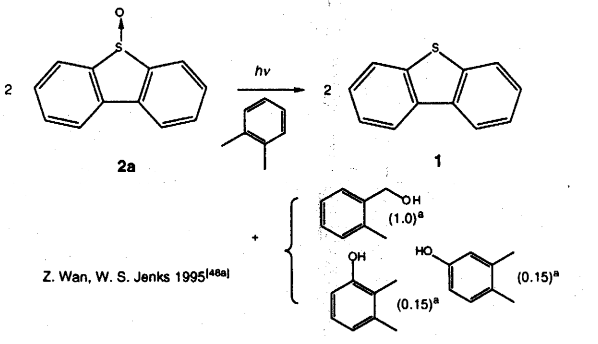
Moreover, dibenzothiophene-$S$-oxides can be deoxygenated photochemically in a number of solvents in the presence of a photosensitizer.[46-48] The triplet energy of DBTO with 61 kcal/mol is quite low,[32] so that a number of photosensitizers can be used. A mechanism for this desoygenation was proposed to involve a dibenzothiophene-$S$-oxide dimer., which gives two molecules of dibenzothiophene and one molecule of oxygen ($O_2$).[46] It had been suggested that singlet molecular oxygen $^1O_2$, $^1\Delta_g$ was the product of this reaction,



G. H. Posner et al. (1973)[46]

Scheme 4

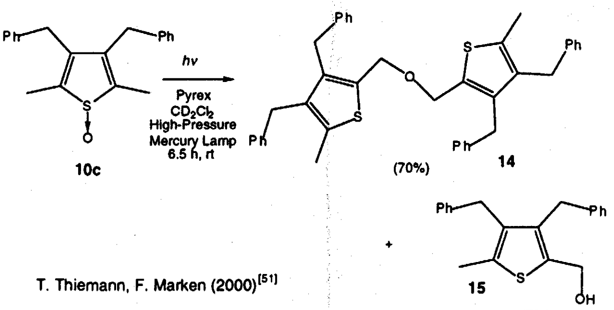
as the irradiation of dibenzothiophene-*S*-oxide in cyclohexene furnished, after reduction with NaI, 2-cyclohexenol in moderate yield. Further photoirradiations in cyclohexene **11** have shown, however, that cyclohexene does not quench singlet oxygen efficiently; moreover, photoirradiations of dibenzothiophene-*S*-oxide in cyclohexane and branched alkanes have furnished cyclohexanol and the corresponding alkanols, so that the idea of an oxenoid reactive oxygen intermediate created under these conditions is now being favored over singlet molecular oxygen.[48, see 49] At wavelengths above 230 nm dibenzothiophene-*S*-oxides are inert towards photodeoxygenation in absence of a photosensitizer, this in contrast to thiophene-*S*-oxides which are readily deoxygenated at much longer wavelengths.[50,51]



Z. Wan, W. S. Jenks 1995[48a]

Scheme 5

a relative ratios

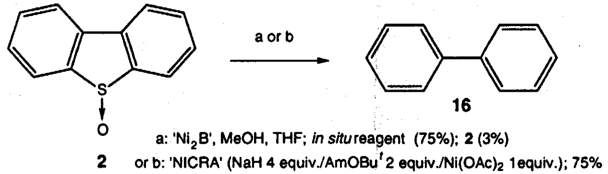


T. Thiemann, F. Marken (2000)[51]

Scheme 6 *Photoirradiation of thiophene-S-monoxides*

The photoreactivity has been used in the hydroxylation and esterification of interior sites within polyolefinic films. A PE film is doped with DBTO at 15 mmol/kg.[52] It is then irradiated with a high-pressure Hg arc lamp at 400W. During this process the DBTO loses its oxygen, thereby reverting back to the dibenzothiophene, oxidizing the PE-film (i.e., hydroxylation). The dibenzothiophene is washed out of the film in a second process. The hydroxylated positions within the film can also be esterified subsequently.[52]

Reductions that do not terminate with a deoxygenation of DBTO to DBT, but which also involve desulfurisation, can be accomplished with nickel catalysts. Nickel boride, a species that is not very well characterised, but is prepared in situ from a nickel(II)salt by reduction with sodium borohydride in a protic medium, does reduce DBTO to biphenyl **16** in 75% yield, where DBT is the by-product (3%).[53] While DBT itself undergoes this desulfurisation with equal ease, $DBTO_2$ gives only a very moderate yield under the same conditions. An analogous reaction is found in the desulfurisation of DBTO with NICRA,[54] a nickel complex prepared from NaH, Am'-ONa, and $Ni(OAc)_2$. When DBTO is subjected to a reaction with 10 mol% NICRA (4/2/1) in the presence of 2,2'-bipyridyl (DME, 65C, 18h), biphenyl is formed in 75% yield. Here, $DBTO_2$ reacts equally well.[55]



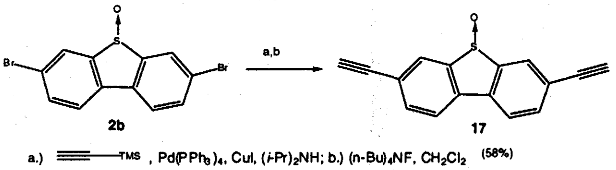
a: '$Ni_2B$', MeOH, THF; *in situ* reagent (75%); **2** (3%)
or b: 'NICRA' (NaH 4 equiv./AmOBu$^t$ 2 equiv./$Ni(OAc)_2$ 1equiv.); 75%

'$Ni_2B$' is prepared according to:

$NaBH_4 + NiCl_2 + 9\ H_2O \longrightarrow$ '$Ni_2B$' $+ 3\ H_3BO_3 + 4\ NaCl + 12.5\ H_2$

Scheme 7 *Reductive desulfurization of DBTO {T. G. Back (1992)[53], P. Caubere (1990)[54]}*

b.) Halogenated dibenzothiophene-*S*-oxides can undergo metal-catalysed coupling reactions as shown in Scheme 8 without deoxygenation.[6]

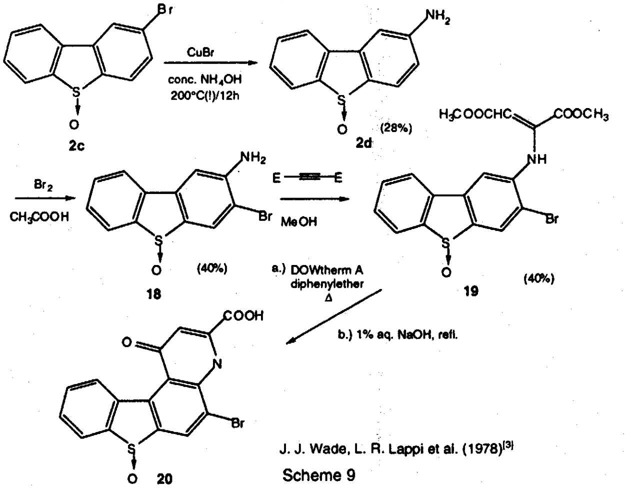


a.) —TMS, $Pd(PPh_3)_4$, CuI, $(i\text{-}Pr)_2NH$; b.) $(n\text{-}Bu)_4NF$, $CH_2Cl_2$ (58%)

(K. Arima, 1999)[6]

Scheme 8 *Pd(0)-catalysed ethynylation of DBTO*

Moreover, DBTOs are relatively stable towards various reaction conditions, as is exemplified by the reaction sequence from 2-bromo-DBTO **2c**, via 2-amino-DBTO **2d**, 2-amino-3-bromo-DBTO **18** and subsequent conden-sation with DMAD to **19** and cyclization to **20**.[3] Here, drastic reaction conditions in both basic and acidic media (e.g., in glacial acid for the bromination of 2-amino-DBTO) have been employed effectively.[3] Even the reduction of a nitro functionality to an amino functionality with Sn in dilute aq. HCl (3-nitro-DBTO to 3-amino-DBTO) could be affected without appreciable reduction of the sulfoxy moiety.[3,58] This stability differentiates the DBTOs from the thiophene-*S*-oxides and the benzo[*b*]thiophene-*S*-oxides (BTOs), especially the non-substituted BTO, which even cannot be isolated in

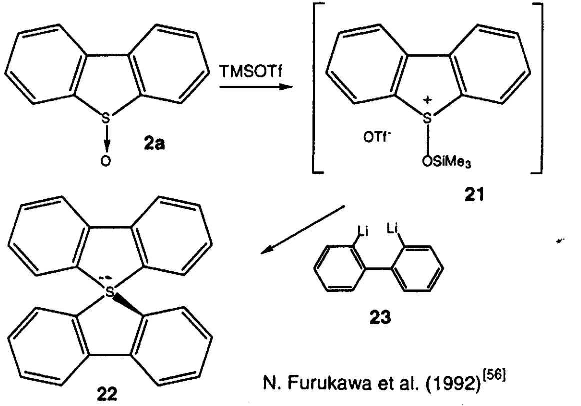


J. J. Wade, L. R. Lappi et al. (1978)[3]

Scheme 9

pure form. Nevertheless, also for DBTOs yields are often quite low in the transformations, often lower than for the corresponding transformations of the dibenzothiophenes (DBTs) themselves. Thus, many authors prefer to oxidize the suitably substituted DBTs to the corresponding DBTOs in the last step of a reaction sequence.

c.) Dibenzothiophene-*S*-oxides can be used as an entry to arylated dibenzothiophenium salts. This approach has been used especially by Hori et al.[5] for subsequent studies on the reactivity of the thiophenium salts towards Grignard and lithium reagents, one of the goals being to produce four C-liganded sulfuranes. While, as Acheson,[18] has shown in an intramolecular reaction, the transformation to the corresponding thiophenium salts do not always proceed, N. Furukawa et al.[56] could react DBTO with trimethylsilyl trifluoromethylsulfonate to the intermediate **21**, which has two good leaving groups on sulfur. Reaction of this intermediate with 2,2'-dilithiobiphenyl **23** yields the at the time first stable C-tetraliganded sulfurane **22**, of which also an X-ray structural analysis could be carried out.



N. Furukawa et al. (1992)[56]

Scheme 10 *DBTO as precursor to tetra-C-liganded sulfurane 22*

## Applications and Use

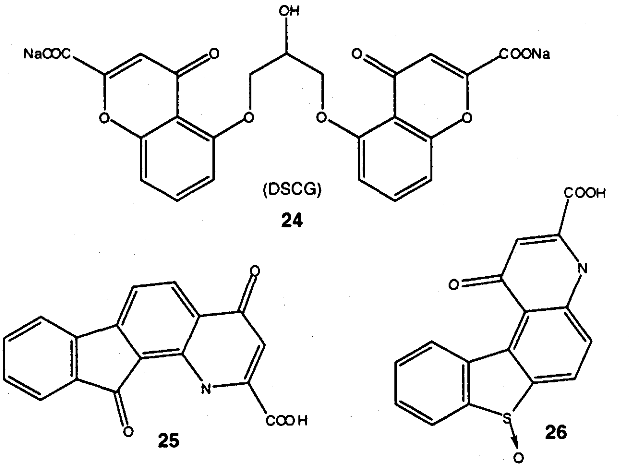
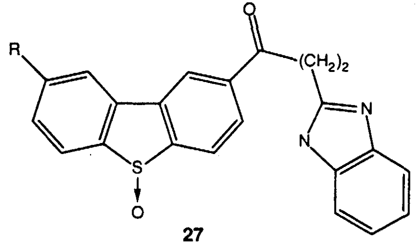


Figure 3

Wade et al.[3] have looked at the possibility of using differently annelated benzooxothienoquinoline carboxylic acids of type **26** as antiallergic agents. Outset of the idea was their similarity to the fluorenone annelated quinoline carboxylic acids of type **25**, which were known to be potent antiallergic drugs. After screening various quinoline annelated dibenzothiophene-*S*-oxides, Wade et al. have found 1,4-dihydro-1,7-dioxo[1]benzothieno[3,2-*f*]quinoline-3-carboxylic acid to be 8 times more potent in the rat passive cutaneous anaphylaxis (PCA) assay than disodium cromoglycate (DSCG) **24**,[57a] a substance that is marketed for the prophylatic treatment of allergic disease states under the trade names, Colimune®, Fivent®, Intal® and Lomupren®, among others.[57b]



**27**

Figure 4

Certain benzimidazolylpropanoyl substituted DBTOs have been reported to have bactericidal and fungicidal activity.[59]

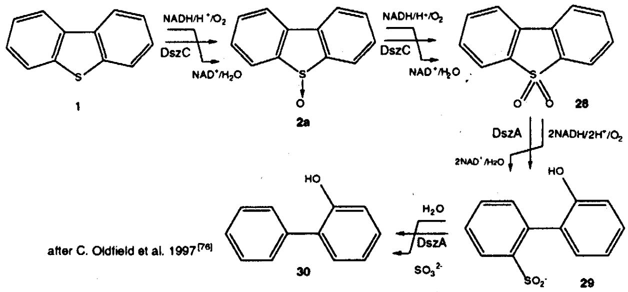
Dibenzothiophene-*S*-oxides have been forwarded as sensitizers in electrophotographic films.[60] Thus, an Al-laminated polyester support has been coated with a component containing a carrier-generating pigment, poly(*N*-vinylcarbazole) and 3,7-dinitrodibenzothiophene-S-oxide to make an electrophotographic film.

There is an isolated report on using DBTO as an antioxidant/stabilizer component together with phenylnapthylamine in lubricating oils.[61] However, there have been reports on using DBTO in combination with amines and ammonium salts as inhibitors of $CO_2$-corrosion in steel pipes.[62]

## Environmental Importance

Dibenzothiophene, higher condensated benzothiophenes and their alkylated derivatives are ubiquitious components in crude oil. These components contribute upon consumption of these fuels a significant amount of the $SO_2$ released into the environment. Government regulations mandate a low sulfur content of fuels. It has been calculated that the refining industry will have to spend up to $37 billion dollars on new desulfurization equipment and a further $10 billion dollars in running costs over the next ten years.[63] Many thousands of polyaromatic sulfur heterocycles (PASHs) are present in hydrotreated diesel fuel and the different alkyl side chains in these compounds affect their reactivity towards both inorganic and enzymatic catalysts, and thus makes the search for a suitable catalyst and for suitable desulfurization conditions extremely difficult. Two basically different approaches have been forwarded – the method of hydrodesulfurization and the method of biodesulfurization. Research in both areas is intense. While great progress has been achieved in the hydrodesulfurization, hydrodesulfurization units are still expensive to build and to operate. Furthermore, the sulfur removal from certain troublesome functionalised dibenzothiophenes has not been solved adequately.

Already in the 1950s US patents had been issued for the microbial desulfurization process. Nevertheless, these processes did not function satisfactorily. Moreover for a commercially viable process, it had to be ascertained that the organisms only degrade the sulfur-containing heterocycles into water soluble materials, but do not 'feed' upon on other components of the fuel. For a workable solution of this problem, the mechanism of the microbial degradation of PASHs, especially of dibenzothiophene (DBT) as a reference compound, needed to be understood. Early on, it had been shown in model (lab) ecosystems that dibenzothiophene can be oxidized microsomally to dibenzothiophene-*S*-oxide. Beijerinckia-[66] and Pseudomonas strains[64] as well as the fungus Cunninghamella elegans[68] are also known to provide dibenzothiophene-*S*-oxide from dibenzothiophene. Recently, a bacterium, Rhizobium meleiloti Orange 1 could be isolated that is capable of growing on dibenzothiophene as the sole carbon and energy source.[69] Also in this case, part of the dibenzothiophene was converted to DBTO.



after C. Oldfield et al. 1997[76]

*Metabolic pathway of DBT by Rhodococcus sp. (strain IGTS8)* Scheme 11

The desulfurization pathway, known as the 4*S*-pathway,[70,71] provided by desulphurization bacteria, has now become understood (and which could only be understood in detail after isolation of the corresponding bacteria)[71] and has been found to be: Dibenzothiophene (DBT) – dibenzothiophene-*S*-oxide (DBTO) – dibenzothiophene-*S*,*S*-dioxide ($DBTO_2$) – (Z)-2-(2'-hydroxyphenyl)ethene-1-sulfinate ($HPESi^-$) – HPEal (see Scheme 11), *i.e.* the sulfur atom of the thiophene core is oxidized progressively, before a C-S bond is cleaved.[71,see also 76] Microbial strains belonging to the genera Thiobacillus[74], Pseudomonas [*v.i.*,72], Corynebacterium[73] and Sulfolobus[74] have been found to be able to metabolize dibenzothiophene in this way. Recently, especially Rhodococcus species[75,76] have been targeted as desulfurization bacteria. In the first step the dibenzothiophene has to be transferred from the oil into the cell of the organism. It seems that in Rhodococcus sp. the molecule is directly transferred to the cell. The desulfurization genes have also been transferred to Eschericolia coli and Pseudomonas putida.[77] The enzyme DBT monooxygenase (DszC) responsible for the oxidation of DBT to DBTO has been isolated and characterized. Its gene has been cloned and sequenced.[78,79] The same enzyme catalyses the subsequent oxidation of DBTO to $DBTO_2$. Thus, while the biochemical pathway of the desulfurization of DBT by such organisms as Rhodoccus is more or less well understood, it is the transfer of this knowledge to the implementation of a viable technology for the desulfurization of large quantitites of fuel that still presents formidable problems. In order to increase the metabolic though-put both the possibilities of modifying the dsz genes as well as changing the host bacteria strain for the genes (strains with different growth rates as well as enhanced metabolic rates) has been looked into.[63,80] With the necessity of developing novel methods for the degradation of DBT and related compounds into more harmless compounds, their microbial desulfurization via dibenzothiophene-*S*-oxide and its derivatives will remain an intense field of study.

## References and Footnotes

1) V. Horak, R. Ponec, *3rd International Congress of Heterocyclic Chemistry*, Sendai 1971, p. 585.

2) a.) K. Fries, W. Vogt, *Justus Liebigs Ann. Chem.* **1911**, *381*, 341; b.) R. K. Brown, R. G. Christiansen, R. B. Sandin, *J. Am. Chem. Soc.* **1948**, *70*, 1748 - 1749; 2c) for a further early preparation of DBTO, see: C. Courtet, C. Pomonis, *Compt. Rend.* **1926**, *182*, 893 - 895 (use of a mixture of $HNO_3$, $H_2SO_4$ and $H_2O$ in a foiled attempt to nitrate DBT).

3) J. J. Wade, E. H. Erickson, R. F. Hegel, L. R. Lappi, T. K. Rice, *J. Med. Chem.* **1978**, *21*, 941 - 948; for a related patent, see: L. R. Lappi, E. H. Erickson (Riker Laboratories, Inc.) DE 2 638 081 (10.3.1977); *Chem. Abstr.* **1977**, *87*, P23 247 w.

4) N. P. Vasilakos, R. L. Bone, W. H. Corcoran, *Ind. Eng. Chem. Process. Des. Dev.* **1981**, *20*, 376 - 379.

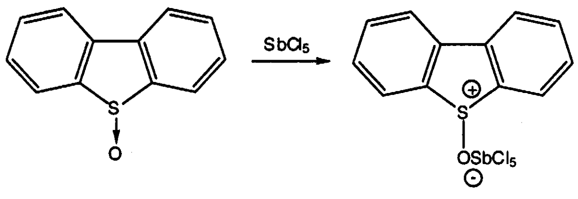
5) a.) M. Hori, T. Kataoka, H. Shimizu, M. Miyagaki, *Chem. Pharm. Bull.* **1974**, *22*, 1711 - 1720; b.) M. Hori, T. Kataoka, H. Shimizu, M. Miyagaki, *Yakugaku Zasshi* **1973**, *93*, 476.

6) K. Arima, MSc thesis, Kyushu University, projected for 2001.

7) R. Liotta, W. S. Hoff, *J. Org. Chem.* **1980**, *45*, 2887 - 2890.

8) M. A. Ledlie, I. V. Howell, *Tetrahedron Lett.* **1976**, 785 - 786.

9) It is known that DBTO forms very stable, isolable complexes with the Lewis acid $SbCl_5$: M. Hori, T. Kataoka, H. Shimizu, K. Onagi, *Chem. Pharm. Bull.* **1978**, *26*, 2811 - 2818.



10) a.) Y. Q. Li, M. Matsuda, T. Thiemann, T. Sawada, S. Mataka, M. Tashiro, *Synlett* **1996**, 461 – 464; b.) Y. Q. Li, T. Thiemann, T. Sawada, S. Mataka, M. Tashiro, *J. Org. Chem.* **1997**, *62*, 7926 – 7936.

11) Y. Watanabe, T. Numata, S. Oae, *Synthesis* **1981**, 204 – 205.

12) a.) J. Castrillon, *Latinoam. Quim.* **1982**, *13*, 102 – 103; b.) for oxidation of DBT to DBTO by iodosyl benzoic acid, see: H. E. Folsom, J. Castrillon, *Synth. Commun.* **1992**, *22*, 1799 – 1806.

13) R. Balicki, L. Kaczmarek, P. Nantka-Namirski, *Liebigs Ann.* **1992**, 883 – 884.

14) T. L. Ho, *Synth. Commun.* **1979**, *9*, 237 – 239.

15) M. Hirano, S. Yakabe, J. H. Clarke, T. Morimoto, *J. Chem. Soc., Perkin Trans. 1* **1996**, 2693 – 2698.

16) T. Takata, W. Ando, *Tetrahedron Lett.* **1983**, *24*, 3631 – 3634.

17) W. Y. Lu, J. F. Bartoli, P. Battioni, D. Mansuy, *New J. Chem.* **1992**, *16*, 621 – 628.

18) R. M. Acheson, M. W. Cooper, *J. Chem. Soc., Perkin Trans. 1* **1980**, 1185 – 1193.

19) N. Kunieda, H. Mochizuka, M. Kinoshita, *Mem. Fac. Eng., Osaka City Univ.* **1978**, *19*, 208 – 210; *Chem. Abstr.* **1980**, *92*, 5664d.

20) E. Bosch, J. Kochi, *J. Org. Chem.* **1995**, *60*, 3172 – 3183.

21) R. Kluge, M. Schulz, S. Liebsch, *Tetrahedron* **1996**, *52*, 5773 – 5782.

22) S. Stavber, M. Zupan, *Tetrahedron* **1992**, *48*, 5875 – 5882.

23) A. Gregoric, M. Zupan, *Vestn. Slov. Kem. Drus.* **1983**, 30, 305 – 312; *Chem. Abstr.* **1983**, *99*, 194749p.

24) a.) E. Baciocchi, L. Mandolini, *Ric. Sci.* **1967**, *37*, 863 - 865; b.) A. A. Humffray, H. E. Imberger, *J. Chem. Soc., Perkin Trans. II* **1981**, 382 – 387.

25) M. Bonchio, V. Conte, M. A. de Conciliis, F. di Furia, F. D. Ballistreri, G. A. Tomaselli, R. M. Toscano, *J. Org. Chem.* **1995**, *60*, 4475 – 4480.

26) R. Kavcic, B. Plesniar, *Bull. Sci., Conseil Acad. RPF Yougoslavie* **1965**, *10*, 177.

27) H. Gilman, D. L. Esmay, *J. Am. Chem. Soc.* **1952**, *74*, 2021 – 2024, but see also: A. H. Schlesinger, D. T. Mowry, *J. Am. Chem. Soc.* **1951**, *73*, 2614.

28) See: T. Akasaka, A. Yabe, W. Ando, *J. Am. Chem. Soc.* **1987**, *109*, 8085 – 8087 and ref. cited.

29) T. Tezuka, H. Miyazaki, H. Suzuki, *Tetrahedron Lett.* **1978**, 1959 – 1960.

30) T. Hirai, K. Ogawa, I. Komasawa, *Ind. Eng. Chem. Res.* **1996**, *35*, 586 – 589; T. Hirai, Y. Shiraishi, I. Komasawa, *J. Chem. Eng. Jpn.* **1997**, *30*, 171 – 173; T. Hirai, Y. Shiraishi, T. Hirai, I. Komasawa, *Ind. Eng. Chem. Res.* **1998**, *37*, 203 – 211.

31) A similar process has been developed by scientists of CALTECH, Pasadena, where benzaldehyde is added. When irradiated with UV light, benzaldehyde is transformed to peroxybenzoic acid, which in turn oxidizes DBT to DBTO and DBTO$_2$. It has been found that under these conditions DBTO converts faster to DBTO$_2$ than DBT to DBTO: A. Paybarah, R. L. Bone, W. H. Corcoran, *Ind. Eng. Chem., Process Dev. Chem.* **1982**, *21*, 426 – 431.

32) W. S. Jenks, W. Lee, D. Shutters, *J. Phys. Chem.* **1994**, *98*, 2282 – 2289.

33) C. P. Butts, L. Eberson, M. P. Hartshorn, F. Radner, W. T. Robinson, B. R. Wood, *Acta Chem. Scand.* **1997**, *51*, 839 - 848.

34) a.) T. Umemoto, S. Ishihara, *J. Am. Chem. Soc.* **1993**, *115*, 2156 – 2164; T. Umemoto, S. Ishihara, *Tetrahedron Lett.* **1990**, *31*, 3579 – 3582.

35) W. Davies, F. C. James, S. Middleton, Q. N. Porter, *J. Chem. Soc.* **1955**, 1565 – 1573.

36) J. A. Hashmall, V. Horak, L. E. Khoo, C. O. Quicksall, M. K. Sun, *J. Am. Chem. Soc.* **1981**, *103*, 289 – 295.

37) I. Rozas, *J. Phys. Org. Chem.* **1992**, *5*, 74.

38) P. Pouzet, I. Erdelmeier, D. Ginderow, J. P. Mornon, P. Dansette, D. Mansuy, *J. Chem. Soc., Chem. Commun.* **1995**, 473 -474.

39) This compares very well with the C-S bond length of 1.787Å calculated at the RHF/6-31G(d,p) level: W. S. Jenks, N. Matsunaga, M. Gordon, *J. Org. Chem.* **1996**, *61*, 1275 – 1285.

40) a.) A. Julg, P. Francois, *Theor. Chim. Acta* **1967**, *8*, 249 - 259; b.) R. M. Schaffrin, J. Trotter, *J. Chem. Soc. A*, **1970**, 1561 - 1565; c.) D. M. Burns, J. Iball, *Proc. R. Soc.*, London, *Ser. A* **1955**, *227*, 200 - 214.

41) J. Giraud, C. Marzin, *Org. Magn. Reson.* **1979**, *12*, 647 – 651 ($^{13}$C NMR). For a depicted MS spectrum of **2a**, see ref. [69].

42) A. C. Lim, *Thesis*, Georgetown University, Washington, D.C., **1972**.

43) T.-L. Ho, C. M. Wong, *Org. Prep. Proc. Int.* **1975**, *7*, 163 – 164.

44) T. Nagata, K. Fujimori, T. Yoshimura, N. Furukawa, S. Oae, *J. Chem. Soc., Perkin Trans. 1* **1989**, 1431 – 1435.

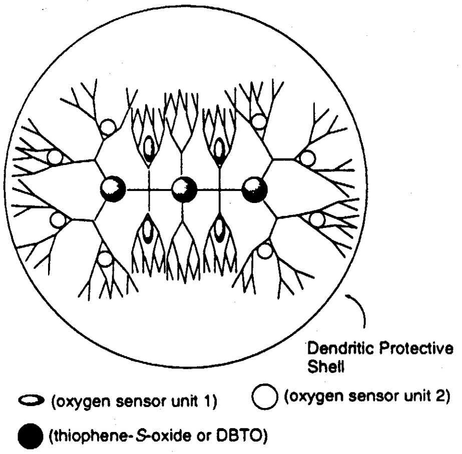
45) a). P. Geneste, M. Bonnet, C. Frouin, D. Levache, *J. Catal.* **1980**, *61*, 277 –278; b.) P. Geneste, P. Amblard, M. Bonnet, P. Graffin, *J. Catal.* **1980**, *61*, 115 - 127.

46) G. M. Gurria, G. H. Posner, *J. Org. Chem.* **1973**, *38*, 2419 – 2420.

47) M. E. F. El Amoudi, P. Geneste, J.-L. Olive´, *J. Org. Chem.* **1981**, *46*, 4258 – 4262.

48) a.) Z. Wan, W. S. Jenks, *J. Am. Chem. Soc.* **1995**, *117*, 2667 – 2668; b.) D. D. Gregory, Z. Wan, W. S. Jenks, *J. Am. Chem. Soc.* **1997**, *119*, 94 – 102.

49) P. Geneste et al. [ref. 47] specifically stated that they were not able to determine the nature of the liberated oxygen in the photodeoxygenation of 3-methyl benzo[*b*]thiophene-*S*-oxide even after careful trapping experiments. In order to verify the nature of the released oxygen, it would be necessary to disallow the formation of any dimer complex of dibenzothiophene-*S*-oxides as well as to exclude any uncontrolled reaction of the primarily oxygen species with solvent molecules. Furthermore, it would be advantageous to allow for a controlled formation of molecular oxygen, should atomic oxygen be the released species in the photodeoxygenation. Plans of embedding an array of separated dibenzothiophen-S-oxides in a protecting dendritic system may be an approach to this problem.



50) For the photoirradiation of DBTO using a uranium glass filter (with a cut-off at about 320 nm), 50% conversion to DBT was achieved, when acridine or benzophenone was used as sensitizer, and only 10% conversion in absence of a sensitizer (all data after 4.25h).

51) T. Thiemann, D. Ohira, K. Arima, T. Sawada, S. Mataka, F. Marken, R. G. Compton, S. D. Bull, S. G. Davies, *J. Phys. Org. Chem.*, in press.

52) C. Wang, R. G. Weiss, *Macromolecules* **1999**, *32*, 7032 – 7039.

53) T. G. Back, K. Yang, H. R. Krouse, *J. Org. Chem.* **1992**, *57*, 1986 - 1990.

54) P. Caubere, *Angew. Chem., Int. Ed. Engl.* **1983**, *22*, 599 - 613.

55) S. Becker, Y. Fort, P. Caubere, *J. Org. Chem.* **1990**, *55*, 6194 – 6198.

56) S. Ogawa, Y. Matsunaga, S. Sato, I. Iida, N. Furukawa, *J. Chem. Soc., Chem. Commun.* **1992**, 1141 – 1442; N. Furukawa, S. Ogawa, T. Matsunaga (Wako Pure Chem. Ind. Ltd.) JP 06 65 251 (8.3.1994); *Chem. Abstr.* **1994**, *121*, P83 054m.

57) a.) J. S. G. Cox, J. E. Beach, A. M. J. N. Blair, A. J. Clarke, J. King, T. B. Lee, D. E. E. Loveday, G. F. Moss, T. S. C. Orr, J. T. Ritchie, P. Sheard, *Adv. Drug Res.* **1970**, *5*, 115; b.) for more details, also see: *Antiasthmatika* In E. Mutschler, *Arzneimittelwirkungen*, Wissenschaftliche Verlagsgesellschaft mbH Stuttgart, 1986, pp.482.

58) M. Carriou, T. Douadi, J. Simonet, *Bull. Soc. Chim. Fr.* **1996**, *133*, 597 – 610.

59) S. G. Donia, *Egypt J. Chem.* **1986**, *29*, 253 – 257; *Chem. Abstr.* **1988**, *109*, 170 308t.

60) M. Hashimoto, K. Sakai, M. Ohta, A. Kojima, M. Sasaki, K. Tsutsui (RICOH Co. Ltd.), JP 79 63.831 (21.5.1979); *Chem. Abstr.* **1979**, *91*, P166 389n.

61) F. L. Loveless, W. Nudenberg (Uniroyal, Inc.), USPat. 4 122 021 (24.10.1978); *Chem. Abstr.* **1979**, *90*, P 74 228k.

62) G. Schmitt, B. N. Labus, H. Sun, N. Stradmann, *8th European Symposium on Corrosion Inhibitors* **1995**, Vol 2, 1113- 1123.

63) For a candid, recent review on the biodesulfurization of fuels, see: D. J. Monticello, *CHEMTECH* **1998**, *28*, 38 – 45.

64) M. Koehler, I. Genz, H. D. Babenzien, V. Eckardt, W. Hieke, *Z. Allg. Mikrobiol.* **1978**, *18*, 67 – 68. (Pseudomonads oil)

65) P.-Y. Lu, R. L. Metcalf, E. M. Carlson, *Environ. Health Perspect.* **1978**, *24*, 210 – 208.

66) A. L. Laborde, D. T. Gibson, *Appl. Environ. Microbiol.* **1977**, *34*, 777 – 782.

67) For Gordonsa sp. strains, see: S. C. Gilbert, J. Morton, S. Buchanan, C. Oldfield, A. McRoberts, *Microbiology* **1998**, *144*, 2545 – 2553.

68) D. L. Crawford, R. Gupta, *Curr. Microbiol.* **1990**, *21*, 229 – 231.

69) S. Frassinetti, L. Setti, A. Corti, P. Farrinelli, P. Montevecchi, G. Vallini, *Can. J. Microbiol.* **1998**, *44*, 289 – 297.

70) J. D. Isbiter, E. A. Kobylinski, *Microbial Desulfurization of Coal* In *Processing and Utilization of High Sulfur Coals* (Y. A. Attia, ed.), Elsevier, Amsterdam 1985, pp. 627 – 641; J. Isbiter, *Biological Removal of Organic Sulfur from Coal* In *Proceedings of Biological Treatment of Coal Workshop*, Sheladia Associates, Rockville, Md., USA, **1985**, pp. 18 – 25.

71) a.) J. J. Kilbane, B. A. Bielaga, *Molecular Biological Enhancement of Coal Biodesulfurization* In *5th Annual Coal Preparation, Utilization and Environmental Control Contractors Conference*, Pittsburg, Pa., USA, **1989**; b.) J. J. Kilbane, Trends Biotchnol. 1989, 7, 97 – 101; c.) I. M. Campbell, *CHEMTECH* **1993**, *43*, 43 – 46; for a detailed presentation of the mechanism of the desulfurization pathway via DBTO, see also: http://www.labmed.umn.edu/umbbd/index.html.

72) M. R. Mormile, R. M. Atlas, *Can J. Microbiol.* **1989**, *35*, 603 – 605.

73) T. Omori, L. Monna, Y. Saihi, T. Kodama, *Appl. Environ. Microbiol.* **1992**, *58*, 911 – 915.

74) a.) F. Kargi, *Biotechnol. Bioeng.* **1982**, *24*, 749 – 752; b.) F. Kargi, J. M. Robinson, *Appl. Environm. Microbiol.* **1982**, 44, 878 – 883; c.) F. Kargi, J. M.

Robinson, *Biotech. Bioeng.* **1984**, *26*, 687 - 690.

75) P. Wang, S. Krawiec, *Arch. Microbiol.* **1994**, *161*, 266 - 271.

76) C. Oldfield, O. Pogrebinsky, J. Simmonds, E. S. Olson, C. F. Kulpa, *Microbiology* **1997**, *143*, 2961 - 2973 and ref. cited.

77) M. E. Gallardo, A. Fernandez, V. de Lorenzo, J. L. Garzia, E. Diaz, *J. Bacteriol.* **1997**, *61*, 7156 - 7160.

78) S. A. Denome, E. S. Olson, K. D. Young, *Appl. Environ. Microbiol.* **1993**, *59*, 2837 - 2843. S. A. Denome, C. Oldfield, L. J. Nash, K. Young, *J. Bacteriol.* **1994**, *176*, 6707 - 6716.

79) C. S. Piddington, B. R. Kodacevich, J. Rambosek, *J. Appl. Microbiol.* **1995**, *61*, 468 - 475.

80) T. Ohshiro, Y. Kanbayashi, Y. Hine, Y. Izumi, *Biosci. Biotechnol. Biochem.* **1995**, *59*, 1349 -1351.