

CLEAN SYNTHESIS OF ENERGETIC MATERIALS USING SOLID-SUPPORTED REACTIONS AND RELATED TECHNOLOGIES

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ABSTRACT

This paper describes progress in the development of clean nitration and azidation methods, based upon the use of solid supports such as clays and zeolites. These cleaner synthetic routes will be necessary to meet the increasingly stringent demands of environmental legislation in the new century. Various routes to achieve these goals are described, the principal subdivisions being: a) nitrations using solid-supported nitrating agents; b) nitrations using catalytic solids, and c) solid-supported azidating agents. Nitrations in clean solvents such as liquid/supercritical carbon dioxide have also been carried out. Using all of these approaches, several chemical classes of precursor molecules, including aromatics, alcohols and amine derivatives have been nitrated, and various types of energetic materials (nitrate esters, nitramines, aromatic nitro compounds and aliphatic azides) have been successfully synthesised. The results show promise for the development of workable methodologies which will overcome the limitations imposed by present and anticipated environmental legislation.

1.0 INTRODUCTION

In previous papers [1-3] the need for cleaner routes for the synthesis of energetic materials, both known and novel, was stated, particularly from the perspective of UK research at DERA. Such work utilises the integrated research facilities in WS3 Department, where disparate disciplines including molecular modelling, chemical evaluation and testing, formulation, scale-up and of course bench synthesis are amalgamated to enable new products and methodologies to be evaluated within the same department. In the work reported here, attention is focussed upon key reactions for the introduction of energetic groups into molecules, namely nitration and, to a lesser extent, azidation. The general strategy is to initially prove the concept of these novel reactions with non-energetic 'model' compounds, with extension in successful cases to energetic counterparts, be they energetic liquids for plasticiser use, solids (e.g. TNT) or energetic polymer precursors (e.g. BAMO, BNMO).

Traditional methodologies for effecting nitration reactions have required the use of strong acids as reagents and reaction media, and it is difficult to dispose of or recycle such media without damaging the environment [4]. Likewise, azidations carried out by current methods require the use of highly polar solvents such as dimethylformamide (DMF) or dimethylsulphoxide (DMSO) which are environmentally unfriendly. Whilst the nitration methodologies developed at DERA [5,6] and based on the use of dinitrogen pentoxide in chlorinated hydrocarbon (CHC) solvents have gone some way towards alleviating these problems, there nevertheless remain unsolved problems connected with the use and disposal of such solvents, which are known to be ozone depleters and therefore detrimental if allowed to escape into the atmosphere. An aim of this presentation, therefore, is to show how, by suitable choice of methodologies for effecting nitration and azidation reactions, the current dependence on environmentally unsatisfactory media and reagents can be minimised, or in some cases eliminated entirely.

2.0 NITRATIONS

2.1 Solid-Supported Nitrations

2.1.1 General

The principles involved in carrying out reactions on solid supports have been detailed elsewhere [7]. Essentially, two classes of reaction system may be employed: a) those where the nitrating agent is bound onto the solid support, or b) those where the solid acts as a catalyst, with the nitrating agent in solution. In either case it is important to realise that the reaction occurs on the surface of the support, not in the bulk solution, a factor which gives these systems a decisive advantage in enabling the use of environmentally benign solvents, e.g. hexane (which are usually poor solvents for nitro compounds and their precursors). In the majority of the work reported here, systems of type a) are employed, although some catalytic zeolite systems have also been studied (see section 2.1.5).

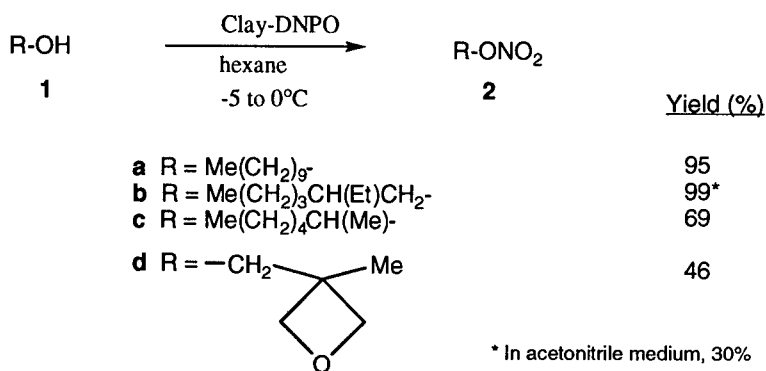
2.1.2 Claycop

In work reported earlier [2], the system comprising an anhydrous transition metal nitrate (copper(II) nitrate) supported on a K10 montmorillonite clay - 'claycop' - first described by Laszlo [8], was evaluated to assess its efficacy in producing energetic compounds, particularly nitrate esters, nitramines and polynitroaromatic compounds. Although this system permitted nitrations to be carried out in an environmentally benign solvent, hexane, the scope of its utility was severely limited, being applicable only to a few nitrate esters with constraints on their structure (i.e. secondary or, better, tertiary nitrate esters). No nitramines could be synthesised and the reagent required additional nitric acid to effect polynitration in aromatic systems. Furthermore, the finding that, in aromatic nitrations, similar results were obtained in the absence of the transition metal nitrate indicated that claycop was not, in fact, the active species in the second nitration step [9]. This work was therefore discontinued and attention turned to the dinitrogen pentoxide (DNPO) systems reported below.

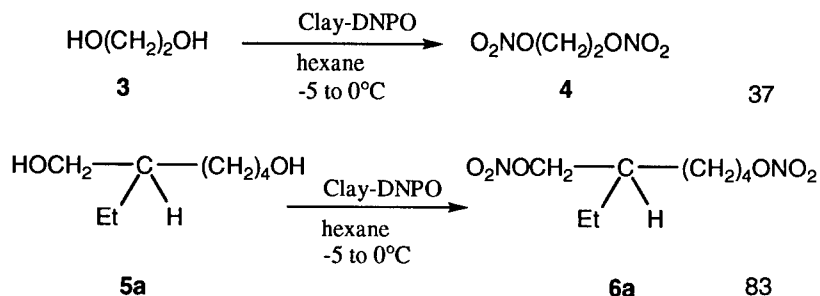
2.1.3 Clay-DNPO

In an attempt to eliminate the use of CHC solvents which had hitherto always been used in DNPO nitrations (DNPO is insoluble in straight-chain hydrocarbons and incompatible with all other known non-halogenated solvents of low polarity), it was decided to investigate the adsorption of gaseous DNPO directly onto K10 montmorillonite clay. This, if successful, would generate a solid nitrating agent with moderated power and enhanced stability compared to DNPO alone. To our satisfaction this turned out indeed to be the case, and K10 clays containing 10-20% by weight of DNPO were readily prepared in this way. These solids were used in several series of nitration reactions, carried out in hexane: firstly with alcohols (Scheme 1) where yields of up to 99% of the nitrate ester products **2a-d**, **4** & **6a** were obtained from the corresponding alcohols (**1a-d**, **3** & **5a**) after reaction periods of 30 min.- 1 hr at the temperatures shown. Workup was simple with mere filtration followed by washing of the spent clay with a solvent compatible with DNPO (currently dichloromethane is used but it is intended to replace this with an

A: Monohydric Alcohols



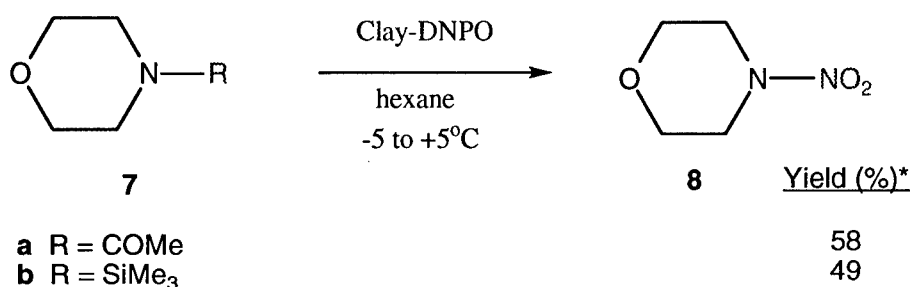
B: Polyhydric Alcohols



Scheme 1: Reactions of Alcohols with Clay-DNPO

environmentally-benign solvent such as a perfluorocarbon). Notably, when a polar solvent, acetonitrile, was used as reaction solvent yields were diminished, suggesting that effects arising on the surface of the clay are important in promoting the reaction, although the nature of these effects is at present unclear.

The clay-DNPO system was also useful in the synthesis of nitramines, and the mononitramine N-nitromorpholine (**8**) was synthesised in up to 58% yield (cf. 0% in the corresponding reaction with

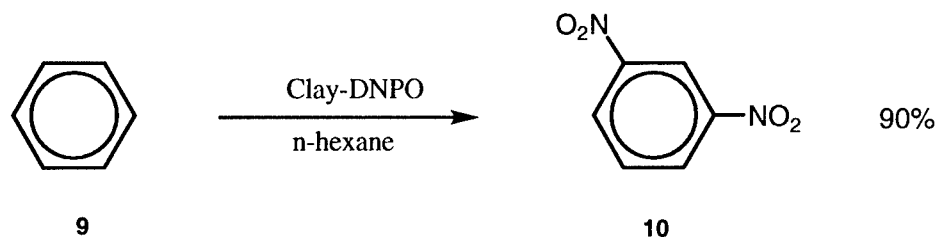


* cf. DCM reaction: 80%[6]

Scheme 2: Synthesis of a Nitramine using Supported DNPO

claycop [2]), from either the N-acetyl or N-trimethylsilyl precursors, **7a** and **7b** (Scheme 2). It is hoped to extend this work to polynitramines at a future date.

Finally, a polynitroaromatic, *m*-dinitrobenzene (**10**), was also synthesised from the hydrocarbon precursor (**9**) using clay-DNPO (Scheme 3):



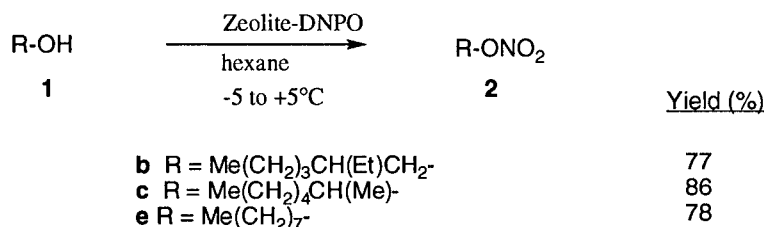
Scheme 3

Therefore these reactions represent a milestone in nitration chemistry whereby for the first time, to the authors' knowledge, a variety of nitrated materials have been made without requiring the use of strong acids or environmentally-unfriendly solvents as the main reaction medium. With further optimisation these reactions should be scalable and meet the requirements of anti-pollution legislation expected in the next few years. The extension of the system to a second type of solid support, zeolites, is now described.

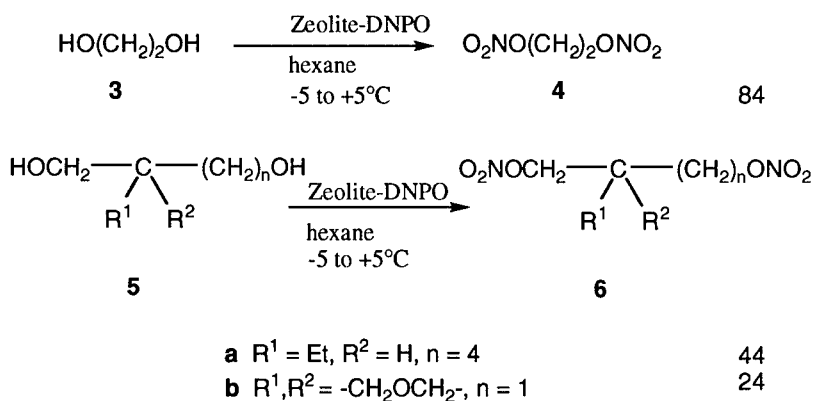
2.1.4 Zeolite-DNPO

In a similar manner to that described in section 2.1.3 above, DNPO was adsorbed onto a small-pore zeolite, H-ZSM-5. Reaction with alcohols in hexane medium gave a variety of nitrate esters in up to 86% yield (Scheme 4). In some cases better yields of nitrate esters were obtained than with clay-DNPO,

A: Monohydric Alcohols



B: Polyhydric Alcohols



Scheme 4: Reactions of Alcohols with Zeolite-DNPO

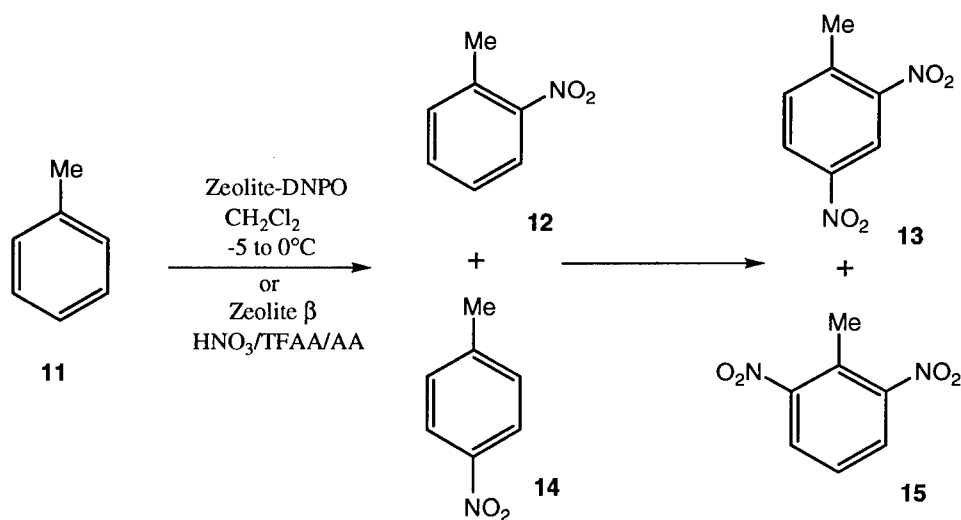
e.g. ethyleneglycol dinitrate (**4**), whilst in others the reverse was the case. Thus the two methods can be considered to be complementary.

In the attempted synthesis of nitramines using this system, however, none of the desired products have been obtained to date, possibly owing to adsorption in the pores of the zeolite. It is intended to re-investigate the synthesis using a medium-pore zeolite of the faujasite type. Aromatic nitration was not investigated with the zeolite-DNPO system (but work on aromatic nitration by DNPO in dichloromethane in the presence of faujasite-type zeolites is described in section 2.1.5). The same comments apply to the exploitation of this chemistry as were made for clay-DNPO (section 2.1.3).

2.1.5 Catalytic Zeolytic Systems

In this section, work is described where the zeolite, of faujasite (protonic) or H⁺-β type, is considered to act primarily as an acid catalyst and thus promote the nitration reactions (aromatic in all cases), rather than as a carrier of the nitrating agent *per se*. Also, the environmental friendliness of these systems is more open to question with the requirement to use CHC solvents (especially dichloromethane, DCM) to dissolve DNPO (faujasite work), or acid anhydrides (especially trifluoroacetic anhydride, TFAA) in conjunction with 100% nitric acid to generate the nitrating species (β work). Nevertheless, the promise of increased regioselectivities from these systems, which by creating fewer by-products may outweigh to some extent the shortcomings of the solvents, means that these systems are still worthy of consideration in the green context.

To focus on one reaction out of many carried out which exemplifies the points mentioned above, the nitration of toluene to 2,4-dinitrotoluene is considered. The two discrete steps **11** → **12** and **12** → **13** (Scheme 5) were investigated separately, then a combined “one-pot” synthesis of **11** → **13** was



Scheme 5: Nitration of Toluene by Zeolite 720-DNPO or Zeolite β-TFAA/AA

studied using both the faujasite/DNPO/DCM and zeolite β/nitric acid/anhydride systems. Initially, the dinitration step (**12** → **13**) is considered as this poses the greatest problem in finding reagents of suitable nitrating strength and also regioselectivity in the position of nitration.

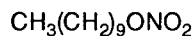
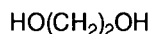
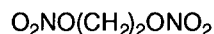
Zeolite H-faujasite 720 (supplied by Zeolyst Ltd.) was found to exhibit the greatest regioselectivity in the dinitration step using DNPO, with a ratio of **13:15** of 4.3:1 attainable (at 0°C, 3 min. reaction time, 94% yield). Taking into consideration the preferred formation of 4-nitrotoluene in the first stage (**14:12** = 0.8 to 0.9; cf. mixed acid *ca.* 0.5), this meant that in the overall process the desired product **13** was formed in preference to **15** in a ratio of 10:1. These effects are rationalised in terms of the dimensions of the pores in the zeolite which are comparable to the molecular dimensions of the benzene ring, thus disfavoured the formation of the more bulky *ortho*-nitrated products [7,10].

A more dramatic influence on the regioselectivity of the reaction (Scheme 5) was observed when the zeolite H⁺-β was used in conjunction with the nitric acid-TFAA system, in the presence of added acetic anhydride (which enhances the selectivity by retarding the reaction rate). Under these conditions, values of the **13:15** ratio of up to 17:1 were obtainable (at -10°C, 2 hr. reaction time, 99% yield). Combined with the selectivities obtainable in the first step (using acetic anhydride only [11]), this meant that selectivities resulting in an overall **13:15** ratio of up to 70:1 were attainable where TFAA was added only in the second stage (or 25:1 if it was used throughout).

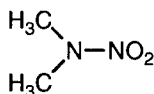
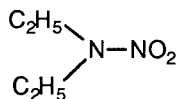
Thus, as suggested above, the increased regioselectivities obtainable using these systems outweigh to some extent the environmental limitations of the solvents and, moreover, with fewer by-products to dispose of at the end of the respective syntheses, they can still be considered in the green context.

2.2 Nitrations in Supercritical Fluids

In earlier work [2], the syntheses of several nitrate esters and one nitramine were reported in liquid CO₂ using DNPO. Selected reactions have now been optimised, and further new reactions studied. In the nitrate ester series, the use of incremental addition of the nitrating agent, DNPO, raised the yield of *n*-decyl nitrate (**16**), from the corresponding trimethylsilyl ether, from 5% to 65%. Also, a new substrate, ethyleneglycol (**17**) was nitrated to ethyleneglycol dinitrate (**18**) in 85% yield in a similar procedure.

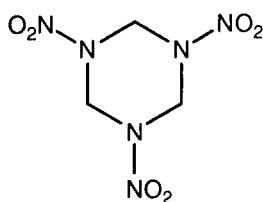
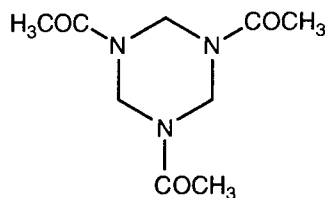
**16****17****18**

Improvements were also obtained in the yields obtainable in nitramine syntheses, in particular by modifications to work-up procedures. Thus yields in the range 45-65% were now routinely obtainable,

**19****20**

and two additional nitramines, N,N-dimethyl- (**19**) and N,N-diethyl- (**20**) nitramines, were accessible by this technology. Although it had been thought [2] that the addition of solvent modifiers, e.g. acetonitrile, to the CO₂ system might improve yields further (observation of the reactions has indicated that they are generally heterogeneous), such modifications were found to have no perceptible effect.

In an extension to the study, the synthesis of a polynitramine, RDX (**21**), was attempted from the triacetyl precursor, TRAT (**22**). DNPO was found to be insufficiently powerful to cleave the N-acyl

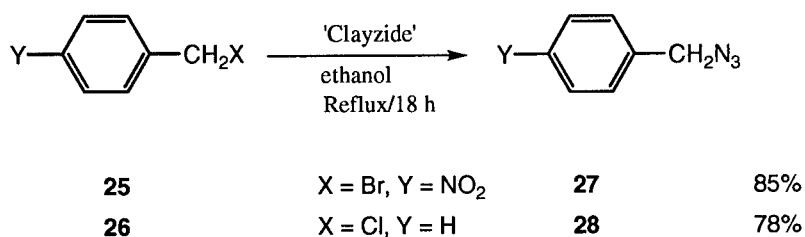
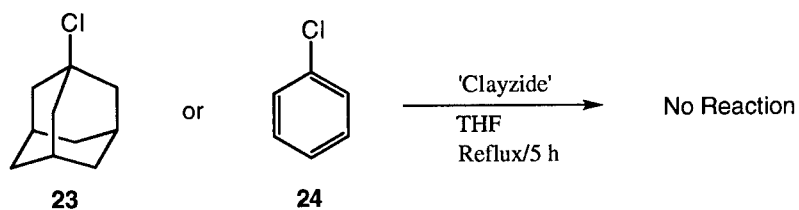
**21****22**

functions, so attention was turned to the nitronium salts NO₂BF₄ and NO₂SbF₆. With the former reagent, a very low yield (*ca.* 1%) of RDX was obtained; thus it is concluded that this does not appear to be a viable route for the synthesis of RDX.

3.0 AZIDATIONS

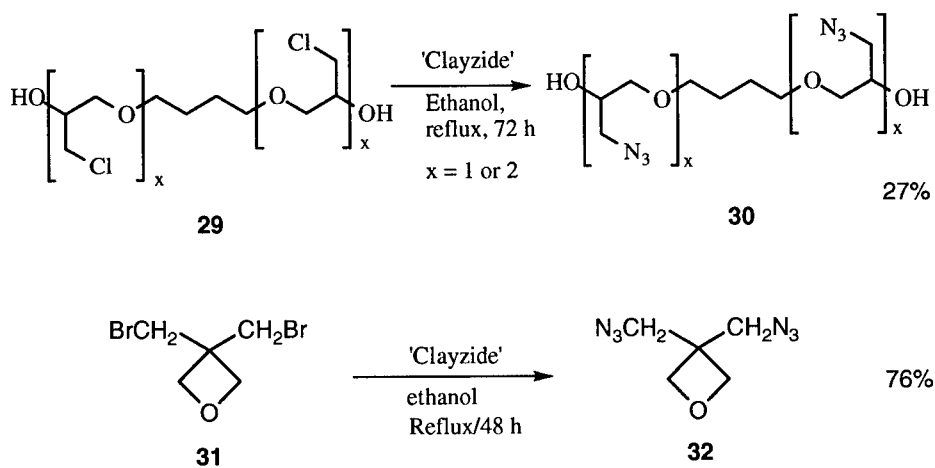
The desirability of replacing strongly polar solvents such as DMF and DMSO in azidation reactions was mentioned above (Section 1.0). Such media are necessary to promote ionisation of the alkali metal azides (e.g. sodium azide) commonly used in the nucleophilic displacement of halides to produce these materials [12]. However, it was felt that in the microenvironment of clay particles, where strong electric field gradients are present [7], such essentially ionic reactions would be facilitated and, indeed, it was found to be feasible to load a K10 montmorillonite clay with sodium azide in a similar way to that employed with transition metal nitrates or DNPO, the novel material so generated being called 'clayzide'.

When clayzide was reacted with molecules containing replaceable halide, organic azide products were formed (Scheme 6). Thus compounds inert to nucleophilic substitution such as 1-chloroadamantane (**23**) or chlorobenzene (**24**) did not undergo substitution, but activated halides such as the benzylic compounds **25** & **26** gave the corresponding azides (**27** & **28**) in high yield in ethanolic medium. It was



**Scheme 6: Azidations by Clay-Supported Azide Reagent ('Clayzide'):
Model Compounds**

also possible to extend the scope of the reaction to energetic polymers or their precursors (Scheme 7): thus polyepichlorohydrin (**29**) could be converted to the GAP pre-polymer (**30**), and bis-(bromomethyl)-



**Scheme 7: Azidations by Clay-Supported Azide Reagent ('Clayzide'):
Oligomers and Polymer Precursors**

oxetane (**31**) gave BAMO (**32**), both reactions again being carried out in ethanol, albeit in somewhat lower yields than the benzylic substrates.

Coincidentally with this work a report appeared of a similar methodology being developed by Varma's group [13], where the clay was first modified by incorporation of a surfactant (creating a pillared clay). This modified clay was then treated with azide and reacted with active halides similarly to the small molecule work detailed above, except that hexane was used throughout as solvent. It is the authors' opinion that, whilst this methodology (essentially under phase-transfer catalysed conditions) may suffice for small molecule reactions, more polar solvents such as ethanol or THF will invariably be required to solubilise macromolecules and their precursors; the two approaches may therefore be regarded as being complementary.

4.0 CONCLUSIONS

A number of approaches towards the cleaner synthesis of energetic materials have been investigated, with the thrust, both in nitration and azidation chemistry, being to eliminate where possible the use of solvents which are harmful to the environment, particularly strong acids, ozone depleters and highly polar solvents. Processes also need to be atom economic [14], i.e. virtually all of the active species on a reagent should be incorporated into the product, so that large excesses of reagent are not required, and if regioselectivity in position of attack (e.g. in aromatic systems) can be achieved, then so much the better. An alternative statement of the penultimate point above is to say that the waste-to-product ratio, as defined by Sheldon [15], should be minimised.

Many of the above aims have now been realised in the work reported here, although further work remains to be done. Specifically, the ability to now perform nitrations, using clay- or zeolite-supported dinitrogen pentoxide, in a medium as inert as hexane is a signal achievement, and the syntheses of further energetic nitrate esters will be investigated/optimised using this methodology. The extension of nitramine syntheses using solid-supported reagents to polynitramines remains a challenge, as does the ability to achieve efficient trinitration of benzene derivatives. Polynitration of benzene derivatives (to the dinitro products) *has* been achieved on solid surfaces but using the solid (zeolite) as a catalyst rather than as a solid-supported reagent. This methodology incurs the penalty of requiring environmentally-unfriendly solvents/co-reactants (e.g. dichloromethane, trifluoroacetic anhydride), and although high regioselectivities are attainable in the position of nitration, which may be beneficial in the synthesis of chemical intermediates e.g. for pharmaceutical or agrochemical application, in the defence context such considerations are of lower importance.

The utility of liquid or supercritical carbon dioxide as a medium for the synthesis of nitrate esters, including polynitrates (e.g. ethyleneglycol dinitrate), and simple nitramines has now been amply demonstrated, although with this medium of course there are limitations to the severity of conditions that

can be employed, since the use of dinitrogen pentoxide dictates that temperatures be kept below 20°C, which is a sub-critical temperature for CO₂ (i.e. supercritical conditions cannot be employed). Also, the scale-up beyond laboratory scale of such reactions remains problematical, with large capital investment being required for process plant.

Finally, in azidations a positive contribution to the environmental friendliness of these reactions has been made through an elimination of the requirement hitherto to use strongly polar solvents such as dimethylformamide or dimethylsulphoxide. The method, using a novel clay-supported azide ('clayzide') is applicable to the synthesis of energetic polymers and their precursors.

5.0 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of the following:- Prof. Keith Smith and Miss Tracy Gibbins, University of Wales, Swansea; Drs Roy Moodie and John Sandall and Mr Llewellyn Lancaster, University of Exeter.

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