



ELSEVIER

Contents lists available at ScienceDirect

Data in Brief

journal homepage: [www.elsevier.com/locate/dib](http://www.elsevier.com/locate/dib)

Data Article

# X-ray diffraction and thermoanalytical datasets of precursors of the $Gd_6UO_{12-\delta}$ phase processed by combined mechanochemical–thermal routes



Gaspar Darin<sup>a</sup>, Kengo Imakuma<sup>a</sup>, Rafael Trautwein Santiago<sup>b</sup>,  
Klebson Lucenildo Da Silva<sup>b,c,d,\*</sup>, Luiz Fernando Cótica<sup>b</sup>,  
Martín Fabián<sup>c</sup>, Jan Valíček<sup>e,f</sup>, Horst Hahn<sup>d</sup>, Vladimír Šepelák<sup>c,d,e</sup>

<sup>a</sup> Nuclear and Energy Research Institute, IPEN/CNEN-SP, 05508-000 São Paulo, Brazil

<sup>b</sup> Physics Department, State University of Maringá, 87020-900 Maringá, Brazil

<sup>c</sup> Institute of Geotechnics, Slovak Academy of Sciences, 04001, Košice, Slovakia

<sup>d</sup> Institute of Nanotechnology, Karlsruhe Institute of Technology, 76344, Eggenstein-Leopoldshafen, Germany

<sup>e</sup> Faculty of Technology, College of Technology and Business in České Budějovice, 37001 České Budějovice, Czech Republic

<sup>f</sup> Faculty of Engineering, Slovak University of Agriculture, 94976 Nitra, Slovakia

## ARTICLE INFO

## Article history:

Received 22 February 2021

Revised 8 March 2021

Accepted 12 March 2021

Available online 18 March 2021

## Keywords:

 $Gd_6UO_{12}$ 

Rietveld refinement

XRD

Thermal analysis

Mechanochemistry

## ABSTRACT

The datasets presented here are related to the research paper entitled “Disordered  $Gd_6UO_{12-\delta}$  with the cation antisite defects prepared by a combined mechanochemical–thermal method” [1]. The datasets complement the findings [1] on the effect of the combined mechanochemical–thermal processing of the stoichiometric mixture of solid precursors ( $3Gd_2O_3 + UO_2$ ) on the formation of  $Gd_6UO_{12-\delta}$  phase. In this article, we provide (i) X-ray diffraction (XRD) data of the  $3Gd_2O_3 + UO_2$  mixture milled for 12 h, (ii) the refined XRD data of the non-milled  $3Gd_2O_3 + UO_2$  mixture after annealing at 1282 °C for 3 h in air, and (iii) the thermogravimetric and differential thermal analysis (TG-DTA) data for non-milled and mechanically

DOI of original article: [10.1016/j.jnucmat.2021.152895](https://doi.org/10.1016/j.jnucmat.2021.152895)

\* Corresponding author at: Physics Department, State University of Maringá, 87020-900 Maringá, Brazil.

E-mail address: [lucenildodasilva@yahoo.com.br](mailto:lucenildodasilva@yahoo.com.br) (K.L. Da Silva).

<https://doi.org/10.1016/j.dib.2021.106972>

2352-3409/© 2021 The Authors. Published by Elsevier Inc. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

preactivated  $3\text{Gd}_2\text{O}_3 + \text{UO}_2$  mixture measured in air at a heat rate of 10 K/min.

© 2021 The Authors. Published by Elsevier Inc.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>)

## Specifications Table

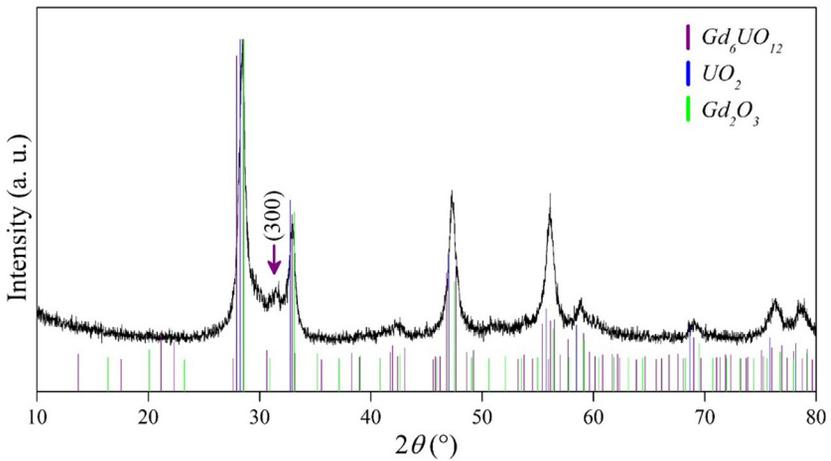
Subject	Materials Science, Materials Characterization
Specific subject area	Nuclear material, Material for nuclear fuel forms, Material for nuclear waste immobilization, Structural analysis, XRD, Thermal analysis
Type of data	Graph
How data were acquired	XRD
Data format	TG-DTA Raw Analyzed
Parameters for data collection	XRD patterns of powdered samples were taken in the range from $10^\circ$ to $80^\circ$ ( $2\Theta$ ) (with angular step of $0.02^\circ$ ) using $\text{Cu K}\alpha$ radiation and a C1702 diffractometer (Shimadzu, Japan) operating in Bragg-Brentano configuration. The TG-DTA was performed in air in the temperature range from $20^\circ\text{C}$ to $1282^\circ\text{C}$ at a heat rate of 10 K/min.
Description of data collection	The Rietveld refinement of XRD data was performed using the <i>FullProf Suite</i> software [2]. The ICSD database [3] was utilized for phase identification.
Data source location	Institution: Nuclear and Energy Research Institute, IPEN/CNEN-SP City/Town/Region: São Paulo Country: Brazil
Data accessibility	With the article
Related research article	G. Darin, K. Imakuma, R.T. Santiago, K.L. Da Silva, L.F. Cótica, M. Fabián, J. Valíček, H. Hahn, V. Šepelák, Disordered $\text{Gd}_6\text{UO}_{12-\delta}$ with the cation antisite defects prepared by a combined mechanochemical–thermal method, J. Nucl. Mater. doi: <a href="https://doi.org/10.1016/j.jnucmat.2021.152895">10.1016/j.jnucmat.2021.152895</a>

## Value of the Data

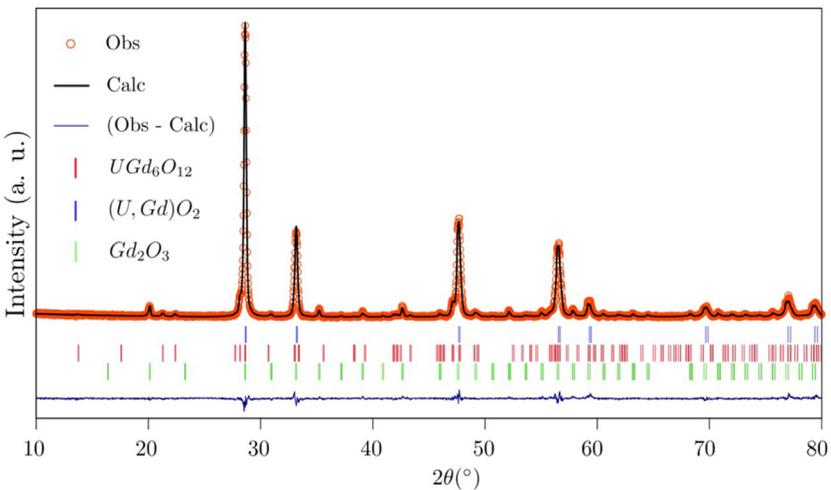
- The datasets are important for a non-conventional mechanochemical preparation of  $\text{Gd}_6\text{UO}_{12-\delta}$ , which is less elaborative, solvent-free, and high-yielded in comparison with the conventional (thermal) synthesis of this nuclear material.
- The data provide the basis for the development of novel nuclear fuel materials.
- The XRD and TG-DTA datasets can guide other materials scientists toward designing novel U-Gd-O systems for nuclear fuel forms and nuclear waste immobilization.

## 1. Data Description

Fig. 1 shows the XRD pattern of the  $3\text{Gd}_2\text{O}_3 + \text{UO}_2$  mixture milled for 12 h before heat treatment. During the high-energy ball milling process,  $\text{Gd}_2\text{O}_3$  and  $\text{UO}_2$  are subjected to a continuous fragmentation accompanied by the reduction of their crystallite size to the nanometer range. The latter is documented by relatively broad XRD peaks shown in Fig. 1. The qualitative XRD analysis reveals that milling of the mixture of individual binary oxides also leads to the *partial formation* of the ternary  $\text{Gd}_6\text{UO}_{12}$  phase. The early stage of mechanochemical synthesis of the  $\text{Gd}_6\text{UO}_{12}$  phase is indicated in Fig. 1 by the presence of a broad XRD peak at the diffraction angle of about  $30.6^\circ$  ( $2\Theta$ ). During the early stages of high-energy milling the reaction precursors are mixed at the atomic level and the new mechanochemical phase nucleates in interfacial regions between the solid reactants during the impact period. During the subsequent thermal treatment



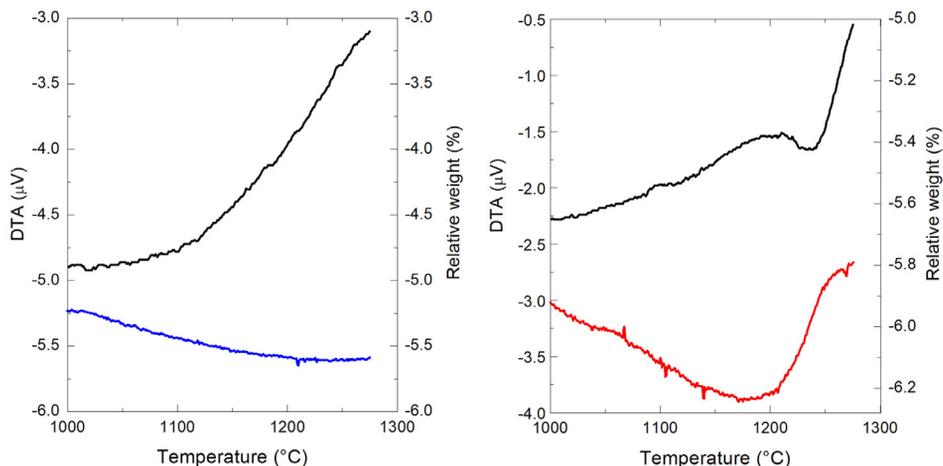
**Fig. 1.** XRD pattern of the  $3\text{Gd}_2\text{O}_3 + \text{UO}_2$  mixture milled for 12 h before heat treatment. The *partial formation* of the  $\text{Gd}_6\text{UO}_{12}$  phase is evidenced by the presence of a broad XRD peak at the diffraction angle of about  $30.6^\circ$  ( $2\Theta$ ) indicated by arrow.



**Fig. 2.** The refined XRD pattern of the non-milled  $3\text{Gd}_2\text{O}_3 + \text{UO}_2$  mixture after annealing at  $1282^\circ\text{C}$  for 3 h in air. The following three phases are present in the sample:  $\text{Gd}_2\text{O}_3$ ,  $(\text{Gd,U})\text{O}_2$ , and  $\text{Gd}_6\text{UO}_{12}$ .

at  $1573\text{ K}$  for 3 h, the *total conversion* of the precursors to the  $\text{Gd}_6\text{UO}_{12-\delta}$  phase takes place [1]. Such a favorable formation of the uranate during the thermal treatment step is a consequence of an accelerated mass transfer and enhanced ionic diffusivity at contact zones between precursors due to reduced diffusion paths as a result of their mechanical preactivation and the partial mechanosynthesis of the target phase.

Fig. 2 presents the refined XRD pattern of the non-milled  $3\text{Gd}_2\text{O}_3 + \text{UO}_2$  mixture after annealing at  $1282^\circ\text{C}$  for 3 h in air. The data document that the solely thermal processing of the mixture does not lead to the complete transformation of educts to the final  $\text{Gd}_6\text{UO}_{12}$  phase. The quantitative analysis of XRD data reveals the presence of the following three phases in the sample: 23 wt.% of  $\text{Gd}_2\text{O}_3$  (ICSD collection code: 230,768), 66 wt.% of  $(\text{Gd,U})\text{O}_2$  (236,072), and 11 wt.% of  $\text{Gd}_6\text{UO}_{12}$  (21,945) [3].



**Fig. 3.** (Bottom) TG and (top) DTA curves for (left) non-milled and (right) mechanically preactivated  $3\text{Gd}_2\text{O}_3 + \text{UO}_2$  mixtures measured in air at a heat rate of 10 K/min.

Fig. 3 shows the TG-DTA curves for non-milled and mechanically preactivated  $3\text{Gd}_2\text{O}_3 + \text{UO}_2$  mixture measured in air at a heat rate of 10 K/min. At about 1200 °C, a significant increase of the relative weight for the mechanically pre-treated mixture is attributed to its oxidation resulting in the complete formation of  $\text{Gd}_6\text{UO}_{12}$ ; *i.e.*, the reaction  $3\text{Gd}_2\text{O}_3 + \text{UO}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{Gd}_6\text{UO}_{12}$  proceeds. This is in contrast to the TG curve of the non-milled mixture exhibiting only a slight increase at temperatures above 1250 °C. The latter is associated with the initial stages of the conventional (thermal) synthesis of  $\text{Gd}_6\text{UO}_{12}$ .

## 2. Experimental Design, Materials and Methods

The synthesis of the  $\text{Gd}_6\text{UO}_{12}$  solid phase requires the presence of two solid simple oxide precursors in the stoichiometric composition ( $3\text{Gd}_2\text{O}_3$  and  $\text{UO}_2$ ) and one gas phase (oxygen); *i.e.*, the overall heterogeneous chemical reaction leading to the formation of  $\text{Gd}_6\text{UO}_{12}$  can be written as  $3\text{Gd}_2\text{O}_3 + \text{UO}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{Gd}_6\text{UO}_{12}$ . At first, the stoichiometric mixture of  $\text{UO}_2$  and  $\text{Gd}_2\text{O}_3$  was preactivated by ball-milling in a Pulverisette 6 mill (Fritsch, Germany) for 12 h at 300 rpm in  $\text{N}_2$  atmosphere at ambient temperature. The milling process was interrupted every 1 h for 5 min (the total number of breaks: 11). A grinding chamber and balls made of stainless steel were used. The ball-to-powder mass ratio was 11:1. The  $\text{UO}_2$  and  $\text{Gd}_2\text{O}_3$  precursors used for the synthesis of  $\text{Gd}_6\text{UO}_{12}$  are products of Nuclear Materials Laboratory at the Industrial Nuclear Center of Aramar (São Paulo, Brazil) and the firm Alfa Aesar, respectively. The mixtures of non-milled and mechanically treated precursors were pressed into pellets at 390 MPa, which were subsequently heated for 3 h at 1573 K in air. XRD patterns of powdered samples were taken in the range from 10° to 80° ( $2\theta$ ) (with angular step of 0.02°) using  $\text{Cu K}\alpha$  radiation and a C1702 diffractometer (Shimadzu, Japan) operating in Bragg-Brentano configuration. The Rietveld refinement of XRD data was performed using the *FullProf Suite* software [2]. The ICSD database [3] was utilized for phase identification. The TG-DTA measurements were performed using a simultaneous thermal analysis apparatus STA 409 C/7/E (Netzsch, Germany). The TG-DTA was done in the temperature range from 20 °C to 1282 °C at a heat rate of 10 K/min. The pelletized samples (700 mg) of both non-milled and mechanically preactivated  $3\text{Gd}_2\text{O}_3 + \text{UO}_2$  mixtures were thermally treated in open platinum crucibles in air.

## CRedit Author Statement

**Gaspar Darin:** Conceptualization, Methodology, Software, Visualization; **Kengo Imakuma:** Investigation, Formal analysis; **Rafael Trautwein Santiago:** Visualization, Investigation; **Klebson Lucenildo Da Silva:** Conceptualization, Supervision, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing; **Luiz Fernando Cótica:** Formal analysis, Supervision; **Martin Fabián:** Investigation, Formal analysis; **Jan Valíček:** Investigation, Visualization; **Horst Hahn:** Supervision; **Vladimír Šepelák:** Supervision, Writing - Original Draft, Writing - Review & Editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships which have or could be perceived to have influenced the work reported in this article.

## Acknowledgments

The present work is supported by the CAPES, the APVV (project 19-0526), and the DFG (project SE 1407/4–2). K.L.S. thanks the SAIA and the Karlsruhe Institute of Technology (KIT) for supporting his research work at the Slovak Academy of Sciences and KIT, respectively. This work benefited from networking activities carried out within the EU funded COST Action CA18112 “*Mechanochemistry for Sustainable Industry*” and represents a contribution to it.

## Supplementary Materials

Supplementary material associated with this article can be found in the online version at doi:[10.1016/j.dib.2021.106972](https://doi.org/10.1016/j.dib.2021.106972).

## References

- [1] G. Darin, K. Imakuma, R.T. Santiago, K.L. Da Silva, L.F. Cótica, M. Fabián, J. Valíček, H. Hahn, V. Šepelák, Disordered  $\text{Gd}_5\text{UO}_{12.8}$  with the cation antisite defects prepared by a combined mechanochemical–thermal method, *J. Nucl. Mater.* (2021), doi:[10.1016/j.jnucmat.2021.152895](https://doi.org/10.1016/j.jnucmat.2021.152895).
- [2] J. Rodríguez-Carvajal, FullProf Suite, Institute Laue-Langevin, Grenoble, France, 2019.
- [3] Inorganic Crystal Structure Database (ICSD), Leibniz Institute for Information Infrastructure, Karlsruhe, FIZ Karlsruhe, 2020.