A step further for the XF® explosive family dedicated to insensitive munitions (IM)

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1 INTRODUCTION

In the 90's, Nexter Munitions developed a low vulnerability technology for large calibres based on the XF® explosive family. One of the first application is the 155 LU211 artillery shell which is currently under mass production for the French army.

The XF® explosives use the melt-cast filling process which is the conventional way of HE shells filling and thus is compliant with the existing worldwide industrial facilities of ammunition producers. The performances and the versatility of the XF® explosives allow a range of applications like bombs, depth charges, field artillery ammunition, main battle tank HE munitions and mortars. In those fields of applications, the main performances of dedicated XF® explosives will be presented.

Nexter Munitions intends not to limit its offer to complete IM products. In order to meet specific customer requests, Nexter Munitions proposes **T**ransfer **o**f **T**echnology based on the XF® explosive filling. As already mentioned, the customers interest in this new technology is the low investment compared to PBX process.

Nevertheless, the main goal of Nexter Munitions is to go a step further in order to facilitate even more the technology transfer. The way to do this is to propose an XF® explosive based on a "ready to melt" concept, called "XF PREMIX ®".

The purpose of the presentation is to give an overview of the R&D activities, and particulary the works conducted in the frame of the XF PREMIX ® approach and the related results as far as the performances and IM signature are concerned.

2 R&D OVERVIEW : NEW ARRIVALS IN THE XF® FAMILY

The objective of the new explosive compositions is to complete the Nexter Munitions ammunition portfolio. Today, the XF EIDS explosive composition used for the 155 mm LU211 IM artillery shell is a very well known composition dedicated for artilleries' large calibre filling with the highest level of safety for users. In order to extend the ammunition offers, Nexter munitions has develop new explosive compositions based on melt-cast proces. The aim of this part is to expose more accurately the development and the properties of new low vulnerability XF**®** explosive compositions.

The first step was to find the technical possible limits of formulation in order to take into account the vulnerability level, detonics performance and cost / vulnerability ratio.
Nexter Munitions R&D department has developed several formulations based on TNT to fulfil these requirements. The aim of this part is to present the targeted performances and the explosive formulation solutions.

2.1 Explosive formulation methodology

The research of optimal conditions require a compromise between the percentage of components used to reach the vulnerability properties, the detonics performances and cost / vulnerability ratio. To fulfil these requirements Nexter munitions R&D department works with the methodology of experimental design. The formulation of explosive compositions is performed with a mixing plan, which allows us to mix various components in a way that they provide a final explosive composition with required properties.

2.2 Explosive formulation optimization

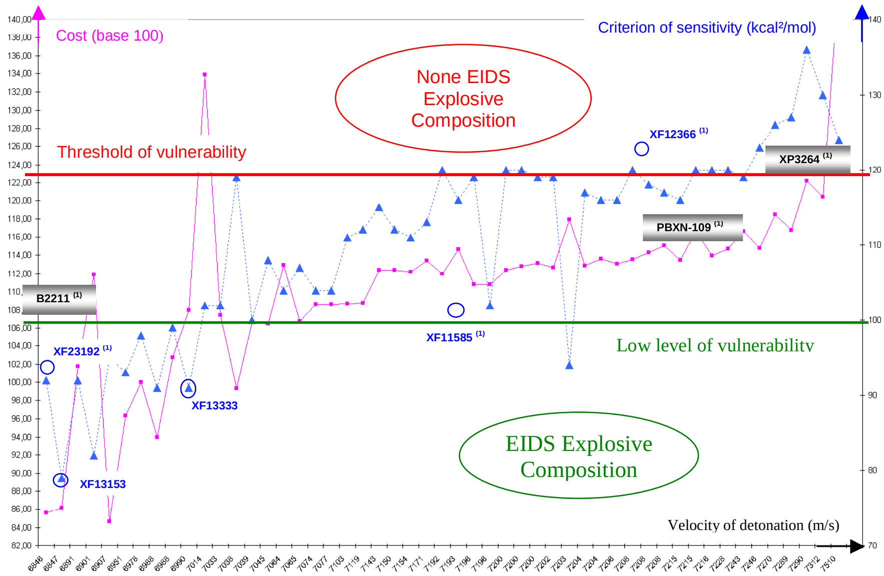
Nexter munitions use performed experimental designs in order to quickly find the optimized formulations. During the formulation step, the use of calculation tools allowed us to define the most relevant compositions.
The detonation properties and theoretical densities were obtained with QUERCY calculation code. The vulnerability was assessed with the help of the following calculation tools:

- the CS (Criterion of Sensitivity), developed by Nexter Munitions on the basis of the CHETAH **[1**],
- and a tool based on COMSOL multiphysics software [4] for the vulnerability aspects.

In order to develop the melt cast compositions, Nexter munitions worked on several ways. The aim is to enhance the detonics performances, to increase the insensitivity level and to find the best compromise between vulnerability and cost. The following paragraphs present these different ways.

2.2.1 Detonics performances approach

To improve the detonics properties, high explosive like HMX is used. By the addition of HMX in a sufficient proportion, the detonics behaviour of the composition is directly linked with this molecule. The detonation velocity is enhanced, whereas the insensitivity level is decreased. So, through the explosive formulations carried out, the table below shows the most interesting trials for detonics aspects.



Caption : the sign [(1)] shows that many composition has been added from the original graph. Only the criterion of sensitivity (CS) has been taken account to place this composition on the figure.

Figure 1: overview of potential explosive compositions

The figure above presents the different calculations realized on formulations potentially candidates. To compare this trials several well known formulations are indicated like PBXN109, XP3264 [5], B2211. These trials show that to improve detonics performances, the properties of insensitivity decreases and the raw material cost increases.

The green line represents the lower limit to have a very low level of vulnerability whereas the blue line represents the upper limit to have an explosive composition which could pretend to obtain an EIDS label (Extrtemely Insensitive Detonating Substance). The area between these 2 thresholds defines an intermediate level of vulnerability.

The explosive compositions mentioned in this figure show the best compromise in terms of cost, detonics performances and vulnerability. Nexter Munitions XF®12366 is the results of the study of this type of compositions. The composition properties are described in the following table.

	Properties			
	Density ρ $g.cm^{-3}$	VoD $m.s^{-1}$	Pcj (kbar)	CS kcal²/mol [1] Base 100
XF®12366	1.75	7215	228	115
XF®13333	1,75	6976	210	100

Table 1: XF®12366 properties

The XF®12366 presents better detonics performances whereas the criteria of sensitivity decrease according to the HMX addition. Nevertheless, this composition is the better compromise and allows Nexter munitions to propose an explosive composition with improved detonics performances.
However, the raw components of this XF®12366 explosive composition were 15% more expensive than the qualified LU211 IM explosive XF® 13 333.

2.2.2 Explosive compositions based on TNMA

To improve the vulnerability level, Nexter munitions developed composition based on TNMA (2,4,6-trinitro-N-Methylaniline). This molecule allowed to obtained a high level of safety use.. The following table presents the TNMA properties compared to the TNT properties.

	TNMA	TNT
Density (g/cm3)	1,67	1,654
Velocity of detonation (m/s)	6770 (ρ=1,5 g/cm3)	6880 (ρ=1,63 g/cm3)
Impact sensitivity	1,4 J	50% go at 5 J
Friction sensitivity	0% at 356 N	0% at 356 N
Electrostatic discharge sensitivity (mJ)	600	600
Bullet Impact	No reaction at 900 m/s	No reaction at 130 m/s

Table 2: TNMA and TNT properties

The following table present performances of the XF®23192 composition.

	Properties			
XF®23192	Density ρ $g.cm^{-3}$	VoD $m.s^{-1}$	Critical unconfined diameter mm	CS kcal²/mol [1] Base 100
	1.75 g.	6830	60	115
XF®13333	1,75	6976	< 120	100

Table 3: XF®23192 properties

Several IM Tests was performed on the XF®23192. The objectives of these tests were to evaluate the IM level of this type of composition. The following table presents the first results obtained for this explosive composition filled into a mock-up called GEMO 3L (steel cylinder with a capacity of 3 liters.

This kind of "tube closed with 2 covers" was especially designed by the French autorities and Industrials to develop new Insensitive Munitions in order to perform IM tests and to compare the recorded results with the data base.

Test	According to	TNT based composition	XF®23192 with TNMA
Bullet impact	ONU 7d)i) standard	No detonation	2/2 No reaction
Fast Cook Off	NF T 70 513 AFNOR standard	No detonation	2/2 No detonation type IV
Slow Cook Off 3,3°/h	NF T 70 515 AFNOR standard	No detonation	1/1 No detonation type V

Table 4: XF®23192 IM test results

The results obtained with the XF®23192 are slightly equivalent than TNT based composition. However the TNMA allows to enhance the thermal stability in comparison with the TNT based composition. This kind of composition allows to propose an another way to formulate thermostable explosive composition and preserve the the level of velocity detonation.

The critical diameter was performed according to the NF T 70-700 AFNOR standard. Cylinder blocks of XF®23192 explosive was ignited by a RDX/WAX/C composition (HCG 95/5/0,5).

Figure 2: Critical Unconfined Diameter configuration (fig, top) and results (fig, bottom)

The critical unconfined diameter of the XF®23192 explosive composition is ∅60 mm.

2.2.3 Explosive compositions based on RDX/NTO/TNT

To find the better compromise between the performance and the cost, Nexter munitions had been working on explosive formulations based on RDX/NTO/TNT. The developments of these kind of compositions are under way thanks to DGA funding.

The RDX addition in an explosive composition allows to improve detonics performances, like VoD and detonation energy. in exchange for which the thermal threat responses, for SCO and FCO tests, are degraded. The objective is to find the best compromise between the thermal response and the detonics performances.

To evaluate the thermal threat responses of several composition and to know the influence by RDX adding , Nexter munitions developed kinetic models allowing to estimate the answer to the Slow Cook Off test and Fast Cook Off test.

These predictive values were realized with a multiphysical code (COMSOL Multiphysics). This calculation code allows to take into account the mechanical and chemical phenomena.. Thanks to experimental designs, we proposed different ratios of RDX/NTO to find the better compromise.

The following figure presents results of calculation for 4 formulations in comparison with the LU211 IM explosive calculation.

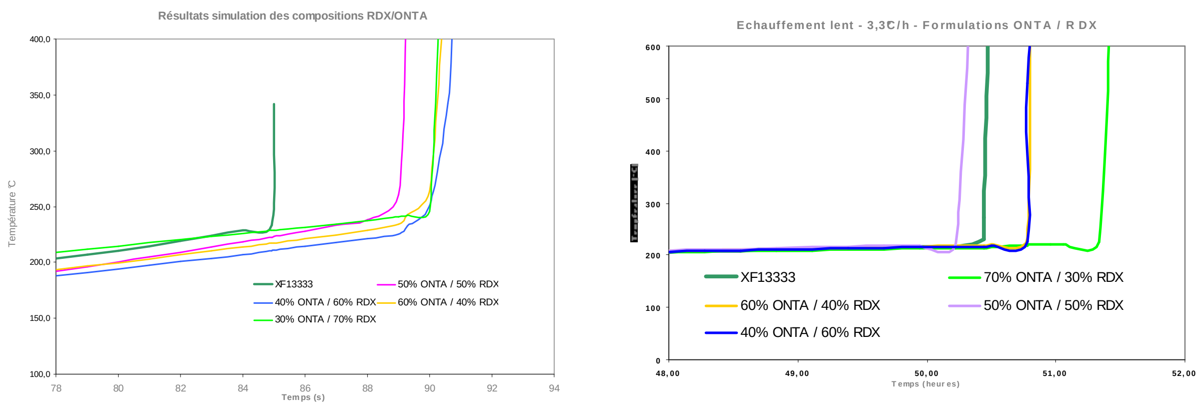


Figure 3: Thermal threat calculation results, left FCO, right SCO 3,3°C/min

SCO	Kinetic thermal reaction (calculated time)	Kinetic thermal reaction (experimental value)
XF 13333	50,4 h	55,3 h (live LU211 IM rounds)
NTO/RDX ~2.33	51,3 h	
NTO/RDX ~1.5	50,8 h	
NTO/RDX ~1	50,2 h	
NTO/RDX ~0,6	51,0 h	

Table 5: SCO results

FCO	Kinetic thermal reaction (calculated time)	Kinetic thermal reaction (experimental value)
XF 13333	85 s	94 s (live LU211 IM rounds)
NTO/RDX ~2.33	89,0 s	
NTO/RDX ~1.5	90,7 s	
NTO/RDX ~1	89,2 s	
NTO/RDX ~0,6	90,5 s	

Table 6: FCO Results

The calculated values are slightly equivalent than the values (calculated and recorded) for the LU211 IM explosive. We choose for the formulation the ratio NTO/RDX ~0,6.

The first results are described in the following table :

	Properties				
	Density ρ $g.cm^{-3}$	VoD $m.s^{-1}$	Pcj kbar	Cost Base 100	CS kcal²/mol [1] Base 100
XF®11585	1,72	7426	223	76	115
XF®13333	1,75	6976 $m.s^{-1}$	210	100	100

Table 7: XF®11585 properties

Other characterisations will be planned. The works are in progress.

2.3 The Nexter Munitions XF family

The objective for Nexter Munitions is to dispose of several EIDS (Extremely Insensitive Detonative Substances) compositions with different level of insensitivity, price and detonics performances. Our approach consisted in both by using experimentally approach and by using predictive software. The following picture illustrates the Nexter Munitions solutions.

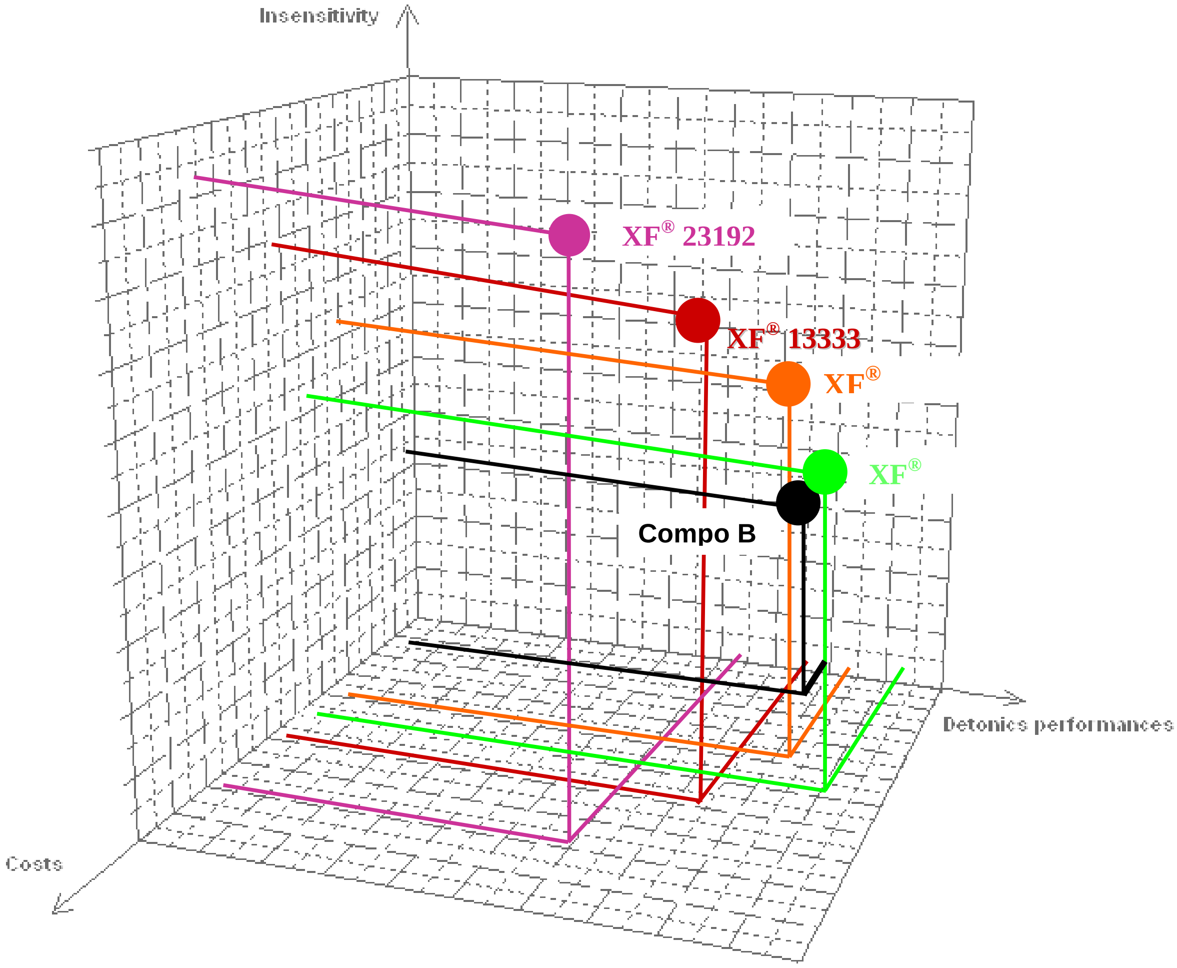


Figure 4: New explosive composition objectives

By developping its explosive compositions portfolio, Nexter Munitions offers a complete range of cost effective XF® compositions with significant low vulnerability properties.

3 PREMIX

The expansion of the EIDS XF® compositions for a large range of munitions led Nexter Munitions, in the frame of Transfer of Technology, to think about the promotion of these new products for our future customers.

3.1 Objective

The main idea was to be able to set directly explosive compositions "ready to use" like composition B. For that Nexter Munitions would like to propose a **Flakes Final Product**.

3.2 Manufacturing process

The following pictures presents the preliminary works to obtain the XF®PREMIX ready to use

Preparation of the melt pour formulation

Manufacturing of flakes

Flakes before cardboard packing

Figure 5: XF® PREMIX process

3.3 XF® PREMIX qualification programme

To give permission for manufacturing this robust product in full production scale, Nexter Munitions carried out the complete qualification programme for the XF 13 333. The following tests and analysis have been performed: filling of HE shells, chemical analysis after cooling, friction and shock sensitiveness, strength under compression, detonation performance and environmental tests [6].

The recorded results are presented in the paragraphs hereinafter.

3.3.1 Filling of HE rounds

Large quantity of 155 mm LU211 IM shell bodies were filled by using the existing industrial facilities.

Figure 6: HE Round filling

To ensure a better control of the filling several batches of TNT and NTO were used during the filling campain.

3.3.2 Chemical analysis after cooling

Thanks to the machining of explosive samples, the quality of the filling has been checked at different places into the block of XF belonging to LU211 shell.

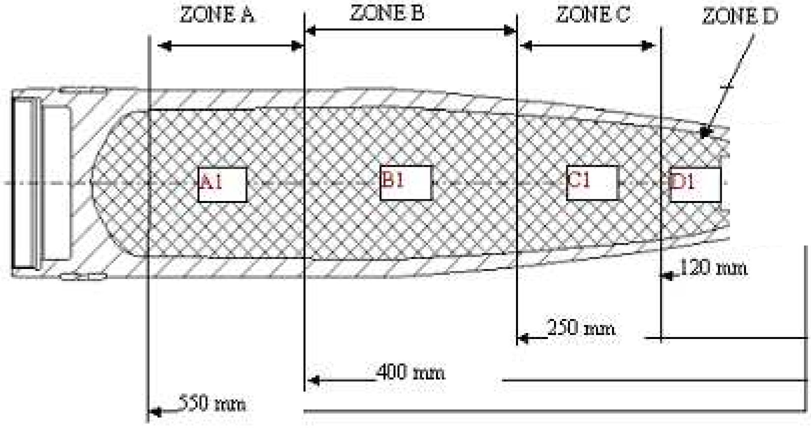


Figure 7: Strenght and chemical XF® block samples – localisation

The recorded results are compared with XF blocks coming from actual mass production.

		
XF® PREMIX Block		XF® Block (mass production)

Figure 8: View of XF® PREMIX blocks after cutting

According to the chemical analysis, the result prove that the composition of XF® PREMIX blocks samples respect strictly the formulation of XF 13333:

	Properties				
	NTO %	TNT %	Wax %	Aluminium %	Density (g/cm^3)
XF®13333 (1) reference	48±2	31±2	7.5±2	13.5±2	1.75
XF®PREMIX (2)	46.6 – 49.4	30.2 – 32.8	5.9 – 7.6	12.5 – 13.5	1.75 - 1.76

(1) fusion tank samples (2) shell samples

Table 8: XF® PREMIX versus XF13333 chemical composition

The results confirm the stability of the XF composition after a second melting.

3.3.3 Friction and Shock sensitivity test

The objective of these basic pyrotechnics tests is to prove that the safety properties and the low sensitiveness of the new XF obtain with flakes are preserved.

	XF13333	XF®PREMIX	AFNOR standard
	50% Go results	50% Go results	
Friction Sensitivity	160 N	190 N	NF T 70 503
Impact Sensitivity	48 J	40 J	NF T 70 500

Table 9: Friction and Shock sensitivity resuts

The recorded results confirm that the filling made with XF® PREMIX is no more sensitive than the one made directly with the different ingredients in the fusion tank.

3.3.4 Strength under compression

Compare to the nominal chatacteristics of the XF® at room temperature, the objective of this test is to confirm the mechanical properties of the block of XF obtained with XF PREMIX ® with a compression loading.

Composition sample	Density (g.cm^{-3})	Stress, max (MPa)	Young Modulus (MPa)	Deformation, max (%)
XF13333	1,767	21,1	2060	1,2
XF®PREMIX	1,757	20,4	2009	1,2

Table 10 : Mechanical properties of XF®PREMIX / XF®

The recorded results confirm the preservation of the mechanical properties. The maximal stress is close to 21 MPa for the explosive block filled with XF® PREMIX.

3.3.5 Detonation performance

The ignition and the detonation of LU211 IM shells filled with XF® PREMIX have been checked in the range of temperature for the operational use (-46°C up to +63 °C).

Figure 9: Set up before ignition test

3 LU211 IM HB have been ignited at the highest temperature

Figure 10: Recovery of the witness plates, test at +63°C

3 LU211 IM HB have been ignited at the lowest temperature

Figure 11: Recovery of the witness plates, test at -46°C

The detonation of the 6 LU211 IM HB shells filled with XF® PREMIX on the complete range of temperature is strictly similar to the detonations recorded with standard LU211 IM shells established during the French qualification.

3.3.6 Environmental tests

Finally, to validate the XF® PREMIX concept, 155 mm LU211 IM HB shells have been filled with flakes and before firing in a 52 caliber weapon system have been subjected to environmental safety tests according to the requirements defined in the Annexe E of the STANAG 4224 4 (Suitability and Safety for minitions in Service). The table bellow gives the different sequences of the tests :

Safety Sequence STANAG 4224 annexe E	
Cond -46℃, 10 shells	Cond +63℃, 10 shells
Logistical Vibrations	Logistical Vibrations
X Ray Inspection	X Ray Inspection
Cold Cycle 7 days	Warm Cycle 7 days
Bounce	Bounce
X Ray Inspection	X Ray Inspection
Drop height 2,1m	Drop height 2,1m
X Ray Inspection	X Ray Inspection
Tactical Vibrations	Tactical Vibrations
X Ray Inspection	X Ray Inspection

Table 11 : Sequential Environment of XF®PREMIX / XF®

In addition, exsudation test (ref CO1-2, hot cycle /24 H during several days up to +71 °C) has been performed on 2 LU211 IM shell. After unscrewing the lifting plug, no exsudate was present between the plug and the booster.
In conclusion, all the LU211 shells filled with XF® PREMIX have stricly the same thermal and mechanical behaviour than those manufactured for the French MOD qualification. Suitability and safety have been confirmed during the firing tests.

Figure 12: Safety Trials of LU211 IM HB shells filled with XF® PREMIX

4 CONCLUSION

In the 90's, aware of the armies need to have Insensitive Munitions, Nexter Munitions has developped a melt-cast explosive called XF®13 333. This explosive composition combined with the new design of 155 mm LU211 artillery shell succeeded in all requirements defined in the STANAG 4439.

Qualified by the services of the French MOD, this ammunition is nowadays under mass production at the filling Nexter munitions plant of La Chapelle Saint Ursin in France.

To promote IM solutions and to enlarge the range of applications from mortar up to bombs or mines, Nexter Munitions masters the Research and Development of new XF explosive compositons based on NTO, RDX, HMX and TNT. Moreover, current works, in the frame of melt cast compositions, are in progress concerning new molecules.

To promote the XF® family nexter munitions has adapted the Compo B flakes process to the XF® composition. The advantages of such an approach are to make easier the approval and storage of the different inert and explosive components. In addition, the XF®Premix simplifies the filling process avoiding any preliminary mixture. By suppressing the handling of explosives during the filling process, the XF®Premix reduces the safety constraints.

5 REFERENCES

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