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Burst tests and volume expansions of vehicle toroidal LPG fuel tanks

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Abstract

This study addresses the prediction of the burst pressures and permanent volume expansions of the vehicle toroidal LPG fuel tanks using both experimental and finite element analysis (FEA) approaches. The experimental burst test investigations were carried out hydrostatically in which the cylinders were internally pressurized with water. The LPG tanks are subjected to incremental internal uniform pressure in the FEA modeling. 2D nonlinear plane models are developed and evaluated under non-uniform and axisysmmetric boundary conditions. For the analysis, the required actual shell properties including weld zone and thickness variations are investigated. Therefore, the results of the burst pressures and volume expansions are predicted and compared to experimental ones.

Key Words: Toroidal shells, LPG fuel tanks, Burst pressures, Permanent volume expansions, Nonlinear failure analysis.

Introduction

Liquefied petroleum gas (LPG) is commonly used as an alternative fuel for the internal combustion engines of the vehicles in Turkey and Europe. The LPG is stored and transported based on Turkish Standards (TS) in Turkey and Economic Commission for Europe Regulation (ECE-R) in Europe. In order to store the LPG in vehicles, the pressure cylinders known as LPG fuel tanks are commonly used and approved by these regulations. The toroidal oval-cross section LPG tanks are designed and manufactured about 25,000 annually by the manufacturer, in Turkey, based on ECE-R67 (1999) and TS 12095-EN 12805 (2004) to be used in Europe and Turkey, respectively. The LPG tanks, low-pressure cylinders since their service pressures is lower than 3.45 MPa (500 psi) (Kisioglu et.al. 2001) can be commercially filled and used in automobile industry. They, equipped with a refillable two-way hermetic valve, are produced as LPG containers and used in vehicles having 45-liter water capacities.

The primary problem of the manufacturer is to determine the burst pressures and volume expansions of the toroidal LPG tanks whose service and test pressures are known by the definitions of the ECE-R and TS rules. The service pressure (SP) is the working (operating) pressure where the tanks are filled and used in industrial applications. The test pressure (TP) is a given pressure that is applied and released at which the permanent volume expansion of the tank must exceed 10% of the initial measured volume (ECE-R67, 1999, and TS 12095, 2004). Finally, the burst pressure (BP) is the maximum pressure at which a toroidal tank can hold without bursting. Therefore, by the definitions of the regulations, the BP of these tanks has to be determined by the manufacturer to confirm the minimum Code requirements.

Although toroidal shell is one of the lesser used shell components, a number of studies have recently been published in literature, which highlights new applications. Galletly (1998) had studied buckling analysis of a complete toroidal shell having elliptical cross-section using the shell buckling programs, BOSOR and INCA. Kaptan and Kisioglu (2007) studied and determined BP and their locations for cylindrical LPG fuel tanks using both experimental and finite-element analysis (FEA) techniques. Kisioglu et. al. (2001) studied and determined BP and their failure locations for the DOT-39 refrigerant cylinders using both experimental and FEA approaches. Kisioglu (2005) studied effects of weld zone properties on the BP and their locations for the DOT-39 refrigerant cylinders. Kisioglu et. al. (2008) studied optimum end closure design for the propane cylinders. Redekop et. al. (1999) had studied stability of fluid-containing toroidal shell and derived some numerical results using both FEA and DQM methods. Wang et. al. (2006) had studied theoretically model analysis and mode shapes for the thin and thick walled pipes and toroidal shells. Therefore, no similar body of knowledge appears to be available in the current literature for BP and volume expansion measurements of the toroidal oval-section LPG fuel tanks.

The purpose of this work is to investigate the BP and permanent volume expansions of the toroidal oval-cross section LPG fuel tanks using both experimental burst tests and numerical analysis. The experimental burst tests are studied using the R&D Lab. facilities of the manufacturer in Turkey. To predict the BP and failure location using numerical approach, the actual shell and weld zone material properties (MPs) including thickness variations of the tanks are investigated. These MPs are used in the numerical modeling process to approximate the BP values obtained by the experimental tests. Therefore, two different types of 2D nonlinear finite element (FE) models, *plane* and *shell*, are developed under axisymmetric boundary conditions.

Design of Toroidal Oval-Cross Section LPG Fuel Tanks

The toroidal LPG fuel tanks are designed and manufactured according to the restrictions of the ECE-R (1999) and TS (2004) Codes considering the SP and TP values. According to these rules, the SP and TP of the toroidal tank are given as 1.75 MPa and 3.00MPa, respectively. In addition, the minimum BP of a toroidal tank is 9/4 times of the TP based on the regulations. The toroidal LPG fuel tanks are usually called by their water capacities as 45-lt tank, and designed as oval-section having 600-mm toroidal diameter and 3.00mm of wall thickness. These tanks are constructed from Erdemir-6842 steel which is hot rolled steel and produced by Erdemir Steel Co. in Turkey. It is 0.18% Carbon content steel and a ductile material suitable for cold forming process used to construct these tanks. The mechanical properties of the Erdemir-6842 steel are defined as 200 GPa of modulus of elasticity, 265 MPa of tensile strength, and about 450 MPa of ultimate tensile strength.

The toroidal LPG tank is designed and manufactured with three main parts: one internal ring and two semi-toroidal shells as seen in Figure 1. Both internal ring and two-semi toroidal shells are manufactured using the spinning process. After spinning processes, these parts are welded circumferentially to form the toroidal LPG tanks as shown in Figure 1. The design parameter definitions of a toroidal LPG tank are presented in Figure 2, such as torus radius (R), the radii of oval-section curvatures, (R_1 and R_2), and height of the oval shell (h). The oval-section of the toroidal shell is designed with the radii of curvatures R_1 and R_2 which are slightly different than each other.

Figure 1. Toroidal oval-cross section of the LPG Fuel tank and its components.

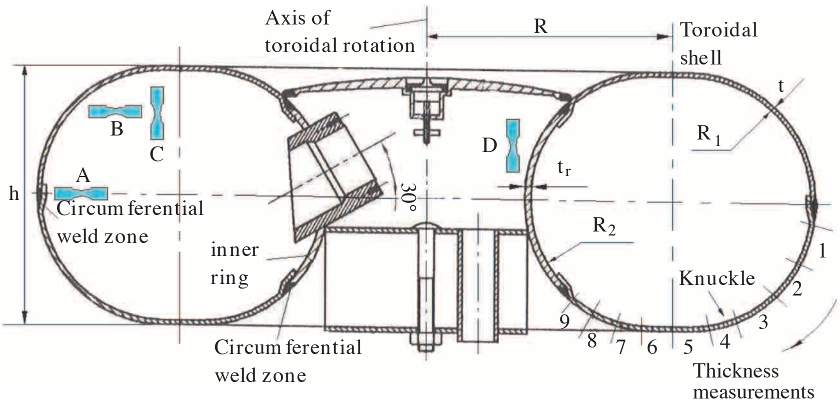

Figure 2. Design of the toroidal LPG fuel tank and its design parameters.

The Experimental Burst Tests

The experimental burst investigations of the LPG tanks are carried out at the R&D laboratory of the manufacturer, in Ordu, Turkey. In order to burst these tanks, the experimental setup is developed as shown in Figure 3(a), the well known hydrostatic burst test technique is used at room temperature. The cylinder specimens, randomly selected from the manufactured stacks and carefully placed in the experiment setup, were completely filled with water, and the pressure was controlled by means of a single acting hydraulic pump. The tanks were placed horizontally during the experiments and air was vented during the filling as seen in the figure. One of the burst cylinders and its burst place is shown in Figure 3(b).

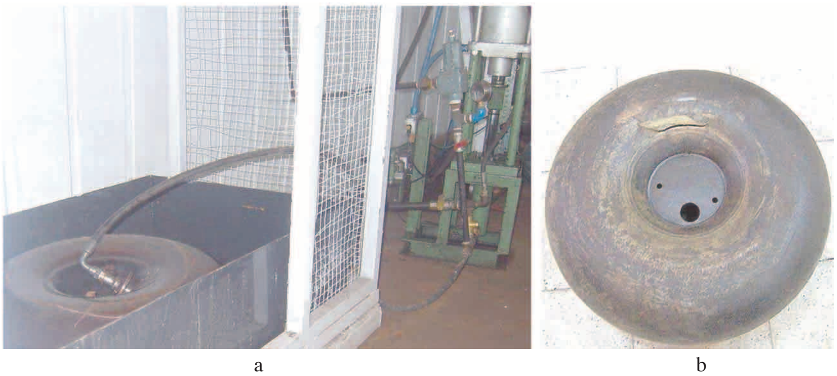

Figure 3. a) The experimental setup and equipments, b) a burst tank.

From the burst experiments, 17 toroidal tanks having 600mm torus diameter and 3.00 mm wall thickness were tested at different times. The BP distribution of total 17 toroidal LPG tanks is shown in a frequency histogram in Figure 4, where frequency refers to the number of occurrences of each BP value in the overall test processes. Since the wall thickness of the Erdemir 6842 blank sheet was variable due to the thickness tolerances, the BP values ranged from a min. of 8.05 MPa to a max. of 8.95 MPa. Therefore, the mean BP values obtained are about 8.56 MPa for the 45-lt toroidal LPG tank with a standard deviation of around 0.220. On the other hand, the initial and max permanent volume expansions were measured to compare and check the permanent volume expansions during the experiments. The min final volume of the burst tank was measured about 51-liter. From these measurements, the min volume expansions of these toroidal LPG tanks were measured more than 11% of the initial volume that confirms the Code requirements.

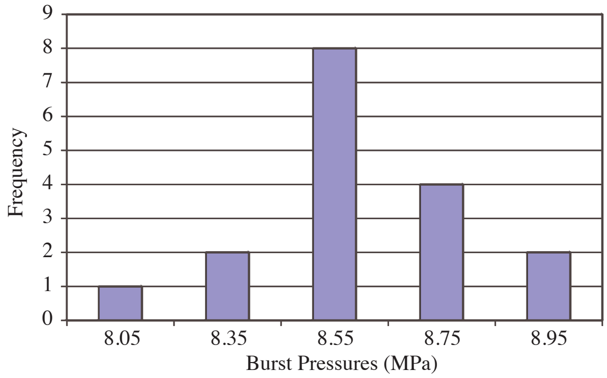

Figure 4. The BP results of toroidal LPG fuel tanks.

Computer-aided burst tests

Computer aided investigations are carried out using ANSYS, finite element computer code, to predict the BP and its location of the toroidal LPG tank. To do this, two different types of non-linear FE models, *plane* and *shell*, were developed using 2D axisymmetric finite plane and shell elements, respectively. To create these FE models and simulate the experimental burst, first, shell MPs and thickness variations of the LPG tanks due to spinning processes are investigated and input to the computer modeling processes. Additionally, after selecting the loading and boundary conditions and appropriate finite elements, the nonlinear axisymmetric 2D FE models were generated and simulated in non-uniform and non-homogeneous conditions.

Investigation of material properties

Tensile test technique is used to investigate the MPs including thickness variations of the LPG tank which is divided into three regions, toroidal shell, weld, and inner ring, as seen in Figure 2. From each region, tensile test specimens A, B, C, and D (Figure 2) were cut out in the directions drawn by a chalk shown in Figure 5. Three of the 17 tanks tested were cut open and one specimen was cut out from each region of each one of these three tanks, providing a total of three specimens from each region all together. The average stress-strain values corresponding to three specimens from each region are illustrated in the figure. Specimens B and C were taken from the same region in circumferential and longitudinal directions, respectively. The average strength of specimens B and C were compared and the weaker one was considered for the simulations. To investigate the weld zone properties, a few tensile test specimens were also taken from the welded zone (region A, see Figure 5) of the assembled cylinders. The average value of specimens "A" represents the weld zone properties. Specimen D was taken from the inner ring of the tanks as seen in the figure. The toroidal shell thickness variations due to the spinning process were measured from the full cross-sectional geometry of the three LPG tanks which were cut open. The measurement procedure, using a micrometer with a precision of 0.001mm, was carried out both "point-by-point" and "by-sliding" the micrometer on the surface. A total of 9 different thicknesses were measured from 9 different points of the toroidal tanks as illustrated in Figure 2. The measured thicknesses are slightly different from the nominal thickness of Erdemir 6842 steel-sheet due to the spinning process.

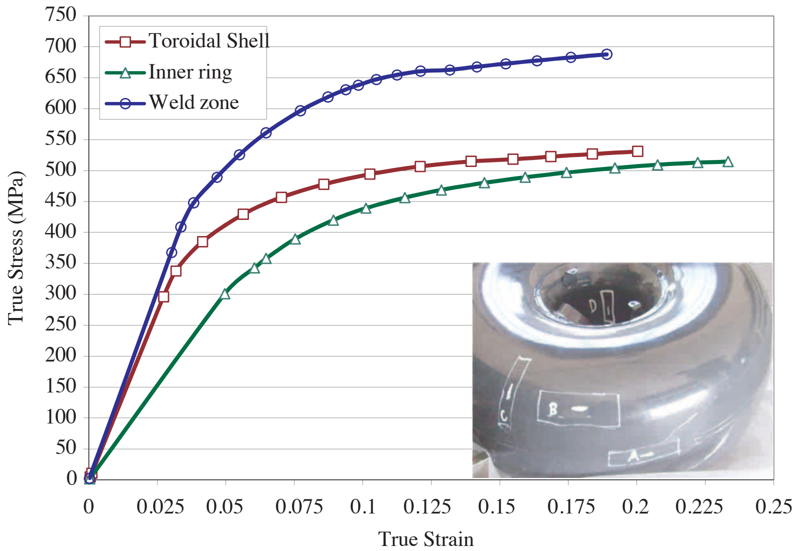

Figure 5. Orientations of tensile test specimens and their average true stress-strain curves.

Development of the non-uniform non-homogeneous model

Non-uniform FE model is constructed using the thickness variation and applying to relevant zones as illustrated in Figure 6. To apply non-uniform wall thickness concepts in the modeling process, the wedge function procedure (Kisioglu et. al, 2001) is applied. On the other hand, different types of the MPs are applied non-homogeneously to relevant regions to create the non-homogeneous FE model. That is; the MPs obtained from each region were used corresponding regions of the computerized FE model that has more than one material property. Therefore, non-homogenous model is consisting of three different types of MPs, toroidal shell, weld zone, and inner ring, including thickness variations which are applied to both plane and shell FEA models as shown in Figure 6.

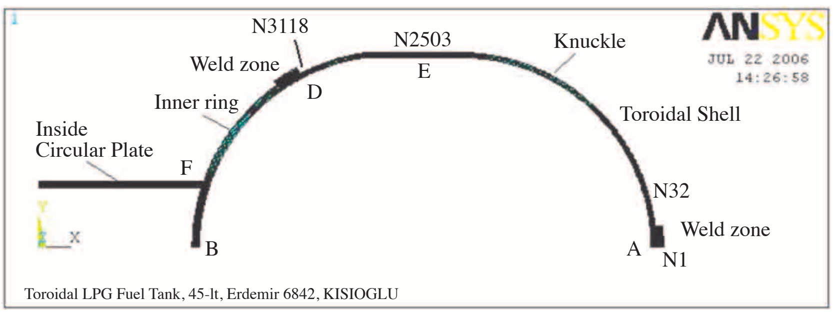

Figure 6. Non-uniform non-homogeneous (plane) axisymmetric FEA models.

The structure of the LPG tank considered here is axisymmetric with respect to the main axes of the torus geometry and with respect to applied load. The 2D axisymmetric FE model is developed by using quarter symmetry without valve slot (Figure 2). Initially, it was assumed that the valf hole located at the inside body of the torus have no affects on the BP values and volume expansions. The axisymmetric boundary conditions are applied to the nodes located on both x- and y-axes. In the 2D FE shell modeling, the mid-surface of the wall thickness is considered to create the LPG tank geometry using the SHELL51 element. The shell FE model has 239 nodes and 238 elements. Similarly, to create the 2D FE plane model, the LPG tank is generated as full section of the tank using the PLANE2 element (ANSYS, 2003). The plane FE model has 6413 nodes and 2764 elements. To determine the BP of these cylinders and define the behavior of the shell structures in the simulations, the tanks are subjected to incremental internal pressure. Initially, the internal pressure was applied incrementally and linearly increased 0.1-MPa loading per step. The loading increment (n) is applied as a function of loading time and gradually increased up to critical point (p_{cr}). When the step is increased from n to n+1 with a smaller loading increment (e.g. about 0.001 MPa), then the loading time reaches to the bursting so that the point is called burst time of the LPG tanks.

Burst failure analysis

Several ways are available to determine the BP and inspect the bursting of the LPG tanks from the FEA simulations. One of them is to observe the structural behavior using the maximum deflections of the tank as seen in Figure 7. To illustrate this, some nodes are selected from critical places of the model. The nodal deflections for the selected points of the *plane* model are plotted as a function of loading time shown in Figure 8. The nodal (Node 2503_Y, at point E on Figure 6) displacement shows nonlinear behavior during the loading time from zero loading state until point "a" that is the burst state. In addition, the nodal behavior shows linear performance after the point "a". Similar ideas can be used for the nodal displacement of the tank (Node 311_Y, at point D on Figure 6). This is the burst time or point where the structural behavior is suddenly changes from non-linear to a linear state (between points a and b) at the loading time of 8.77 MPa, at which the toridal LPG tank is burst. Since, the FE modeling condition is altering stable state.

One of the other ways to analyze the burst failure of the tank is to examine the nonlinear equivalent stress (von Mises stress) values that were compared to the tank MPs as seen in Figure 9. The nodal maximum stress value (at Node 3118 at point D, Figure 6 and 9) was obtained higher than the given ultimate tensile stress value of the actual shell material. The burst failure location of the toridal tank was obtained from the FEA very close to the welded joint of the toroidal shell and the inner ring at point D (see Figure 6) that is the same location obtained from the experimental tests (see Figure 5).

Permanent Volume Expansions

When these tanks are pressurized hydrostatically, the volume of the LPG tanks are ballooning permanently in both x and y directions as seen in Figure 10. Consequently, permanent volume expansions of the LPG fuel toroidal tanks are measured from both experimental tests and computer aided FEA simulations. The purpose of the measurement is to verify the computer aided modeling and comply with the Code definitions. Based on the regulations, the permanent volume expansions of these tanks must exceed 10% at least of initial volume at the burst time. Therefore, the volume expansions are measured after the burst tests in both torus circumferential and axial directions. The magnitudes of the torus axial and circumferential expansions are designated with "a"

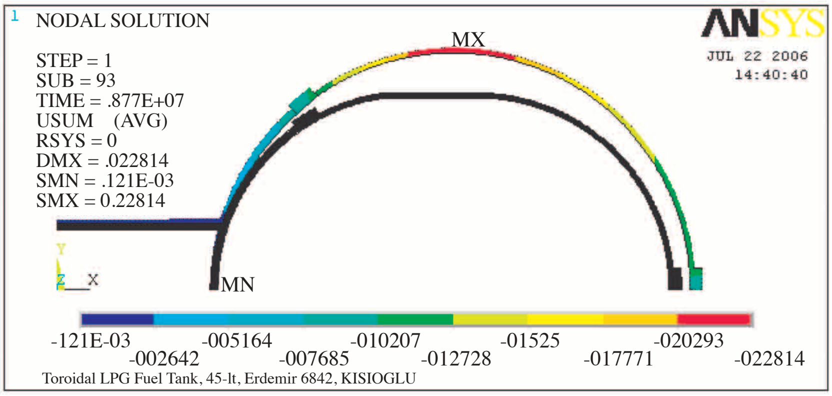

Figure 7. Max deflections (burst deflection) of the LPG tanks.

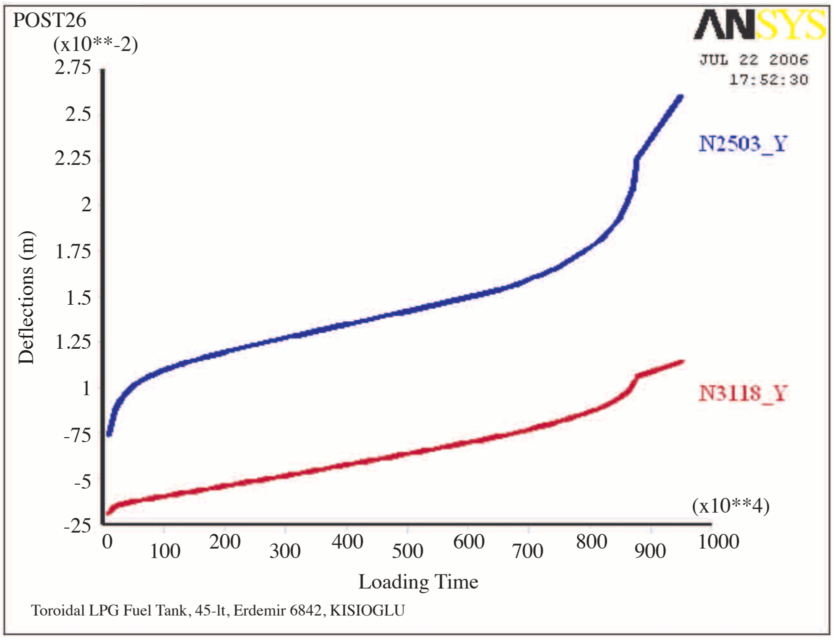

Figure 8. Nodal deflection of selected nodes of the LPG tanks.

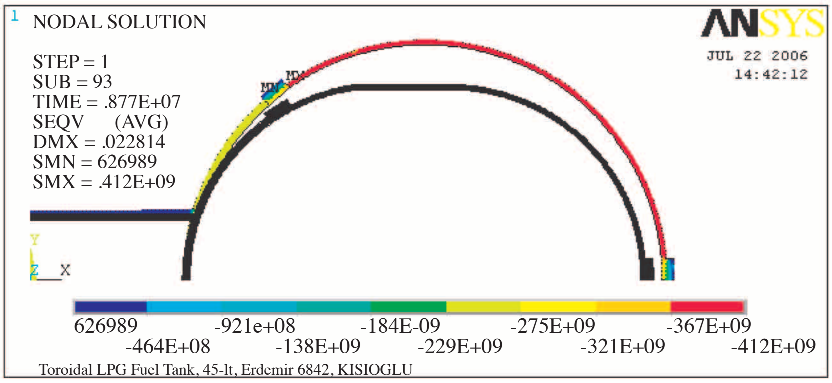

Figure 9. Nodal equivalent stresses (von Mises) of the LPG tanks.

and "b", respectively. The magnitudes of "a" and "b" expansions were obtained from FEA simulations about 26.31mm and 12.79mm, respectively, as illustrated in Figure 10. Similarly, the magnitudes of "a" and "b" extensions were measured using 5 burst tanks during the experimental tests and the measurement distributions are presented in Figure 10.

Volume Expansion Measurement				
Test Specimens	Experimental Measurements		FEA Simulations	
	a (mm)	b (mm)	a (mm)	b (mm)
1	25	13		
2	27	14		
3	26	14	26.31	12.79
4	24	12		
5	27	11		

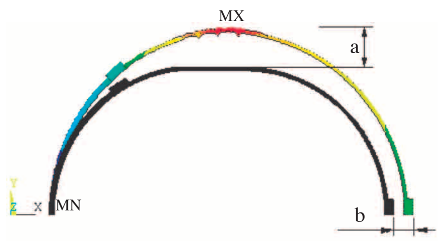

Figure 10. The permanent volume expansions and the measurement distributions.

Conclusions

The case of thin-walled toroidal oval-cross section LGP fuel tanks subjected to an incremental internal pressure to determine the exact BP and permanent volume expansions were studied using both experimental and computer aided FEA approaches. The axisymmetric 2D FE models having a non-uniform geometries and non-homogeneous MPs were developed and simulated in the nonlinear field. Based on the generated results, the following conclusions can be made:

1. Good agreement between the experimental burst and corresponding non-linear axisymmetric FEA simulations was found about the BP values. The BP values of the toroidal oval-section LPG tank were obtained about 8.77-MPa (Figures. 7 and 9) which is close to the mean BP value, 8.56-MPa, of the experimental ones (Figure 4). These values are obtained higher than the 9/4 times the TP value of the torus tank and also confirming the Code regulations.

2. Good agreement was also found about the permanent volume expansions measured from both experiments and simulations as presented in Figure 10 and complied with the Code definitions. The final volume of the 45-liter toroidal tank was measured about 51-liter after the burst test so that the min volume expansions of the tank were measured more than 11% of the initial volume.

3. The actual toroidal shell and weld zone MPs including wall thickness variations were well specified in this study and successfully adapted into the ANSYS computer code. Additionally, the behavior of incremental internal pressure loading was applied successfully and remained linear about 95% of the loading time.

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