Proceedings of the 17th International Symposium on the Packaging and Transportation of Radioactive Materials
PATRAM 2013
August 18-23, 2013, San Francisco, CA, USA

IMPROVING THE SAFETY OF BOLTING SYSTEM - USE OF THE ULTRASONIC TEST STRESS TIGHTENING METHOD

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ABSTRACT

For the transport and interim storage of nuclear material TN International proposes to its customers a wide range of licensed cask design.

The new transport & interim storage flask (TN®24E) for the German market with an advanced design to high efficiency has required to tighten the trunnion screws to a very high level of stress.
New solutions for tightening these screws in compliance with all the German requirements in terms of standards and State of the Art had to be developed for this reason. Until now, the usual method to control the screw tightening implemented everywhere on a cask (for the bolts of lids, trunnions and protective covers) is to measure the torque using a torque-meter / torque-wrench (or equivalent).
The qualification of this method leads to the implementation of typical accuracy around 5% on the tightening torque which corresponds consequently to 20% on the actual tightening force due to the uncertainty of the grease friction coefficient. That defines also the type of acceptable tightening equipment.

In order to avoid damaging the screws due to an over-tightening, the accuracy of the force measurement had to be limited to 6.5% (instead of the usual 20%).
The new method of control - The Ultrasonic Test stress tightening method - complies with this requirement.
This technology is based on the measurement of the travel time of the ultrasonic wave along the elongating screw during the tightening. An ultrasound sensor is thus positioned inside a socket in order to measure the screw travel time in live. The information of the travel time combined with the calibration coefficient of the screw allows measuring the actual tightening force applied.

The Ultrasonic Test stress tightening method is applicable for assembling the trunnion, control the tightening force after the loading test and the recurrent inspection of the cask.
It was qualified by TN international and approved by TÜV Rheinland as expert of the German authority BAM to guaranty compliance with the guide BAM-GGR 011.

This paper describes this new method, the first results from qualifications and its application within the TN®24E flask and the safety and design advantages.

INTRODUCTION

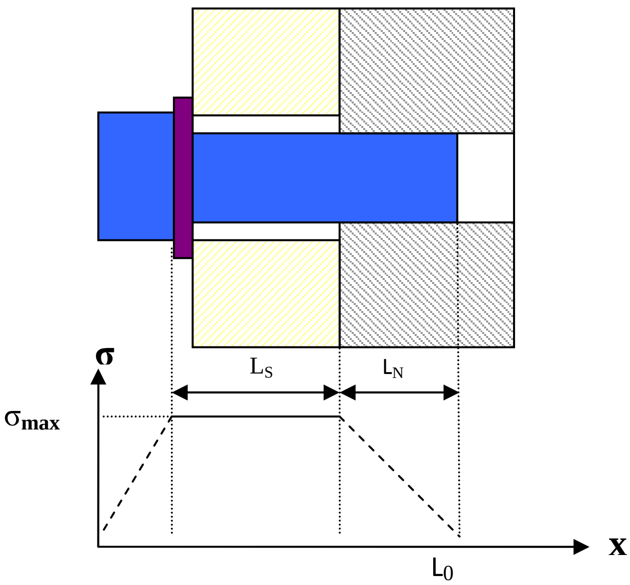
TN®24E advanced design of TN®24 product range from TN International was designed to be loaded with UOX and MOX PWR spent fuel assembly in German power plant. The internal arrangement includes 21 lodgments. The maximum dissipating capacity is **39 KW.**

Its trunnion system used for handling operations is compliant with KTA 3905 <6> and VDI 2230 <7> requirements. Since standard tightening method with torque wrench leads to a great dispersion on the screw load (20%), a tightening method based on ultrasonic waves was developed to better control the preload and to reach very high stress in the screws. Reduction of the bolts number is one of the great advantages of this new approach.

The qualification of this new method was monitored by TÜV Rheinland as expert of the German authority BAM. All these activities were performed in the frame work of BAM-GGR011 requirements <5>.

PRINCIPLE OF THE METHOD

The control of the strain by this ultrasonic (US) method is based on the fact that **variations in strain affect the screw length measured by the US travel time along the screw**.



- L_S *: equally loaded length*
- L_N *: engaged length*
- L_0*: total length*
- *σ: Strain*

Figure 1: One dimensional stress model of a screw assembly <1>

Considering a one dimensional model for the calculation of the strain as explained in <1> (see fig.1), the relationship between the travel time variation (dt) and the stress (σ) in a segment dx is given by:

$$dt = \left[1 + \left(E^{-1} - Caxis\right) \cdot \sigma\right] \cdot V_0^{-1} \cdot dx \quad (1)$$

With:

- V_0: Wave speed in stress-free condition of the screw
- C_{axis}: Acousto-elastic constant considered the strain effect for the wave speed
- E: Young’s modulus

The **effect of unequally strain distribution** is considering in <1> by mathematical models or US measurements on reference screws.

The **effect of temperature** is considered in <2> by:

$$\Delta\sigma = \frac{E}{C_{axis} \cdot t_0} \cdot \left(t - t_0 - \Delta_{tT}\right) \quad (2)$$

With:

- $\Delta\sigma$: Strain change
- t_0: Travel time in strain-free condition (reference travel time)
- t: Travel time in strain condition
- Δ_{tT}: Effect of temperature on the travel time

Under consideration of the **strain distribution by reference screws**, for **constant temperature conditions** and the fact that the US has to pass through the screw two times:

$$\frac{t - t_0}{t} = \left(E^{-1} - C_{axis}\right) \cdot \frac{L_0 + L_S}{2 \cdot L_0} \cdot \frac{4 \cdot F_{MAX}}{\pi \cdot D^2} \quad (3)$$

$$\frac{t - t_0}{t} = K \cdot F_{MAX} \quad (4)$$

With :

- F_{MAX}: Force applied in the screw
- D: Diameter of the screw
- $K = \left(E^{-1} - C_{axis}\right) \cdot \frac{2 \cdot \left(L_0 + L_S\right)}{L_0 \cdot \pi \cdot D^2}$ (5)

K is the calibration coefficient of the screw which links the tightening force to the travel time. Its experimental determination is explained in the next section.
The fig.2 visually shows the behaviour of a screw under loading conditions.

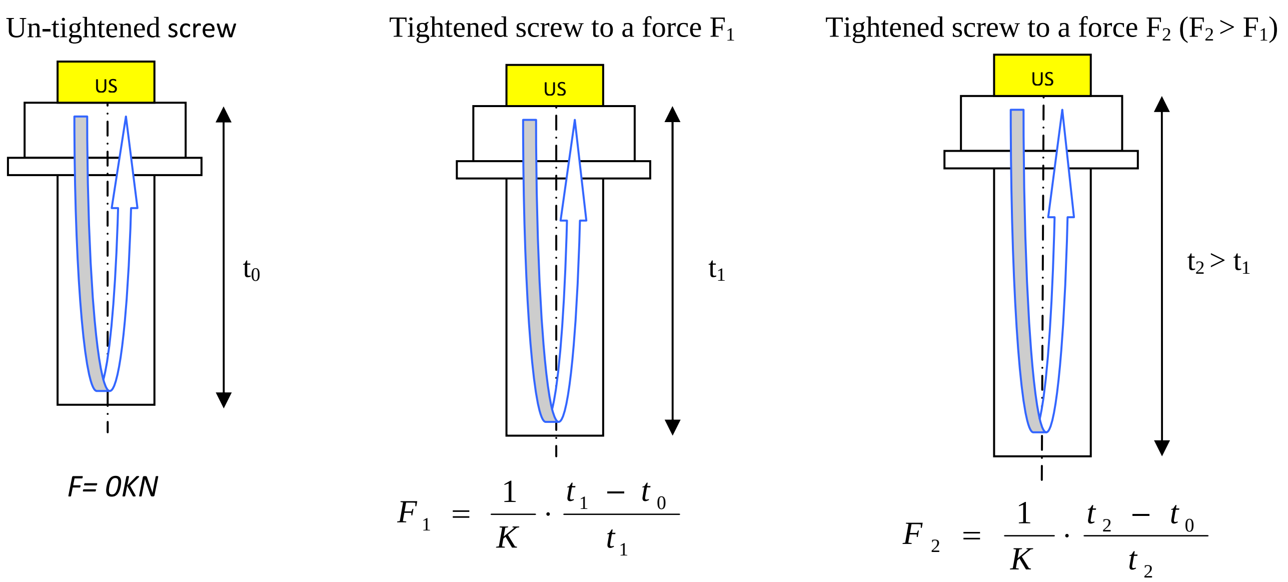


Figure 2: Visualisation of the behaviour of a screw travel time under loading condition

DETERMINATION OF THE CALIBRATION COEFFICIENT OF A SCREW

To guarantee an identical strain distribution to the flask conditions, the calibration coefficient of the screws is determined using a **mock-up which is fully representative of the flask** (same materials, heat treatment conditions, dimensions, grease …). See fig.3 and fig.4.

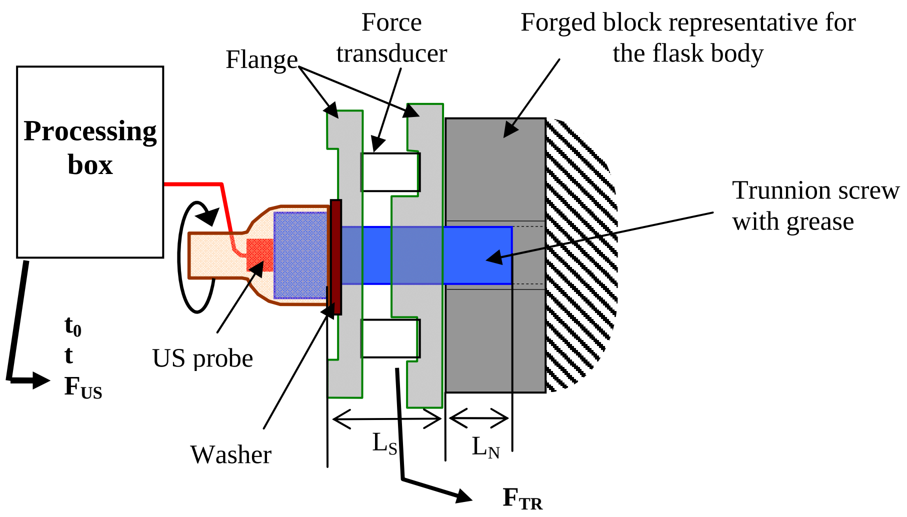


Figure 3: Sketch of the mock-up for the calibration of the screws

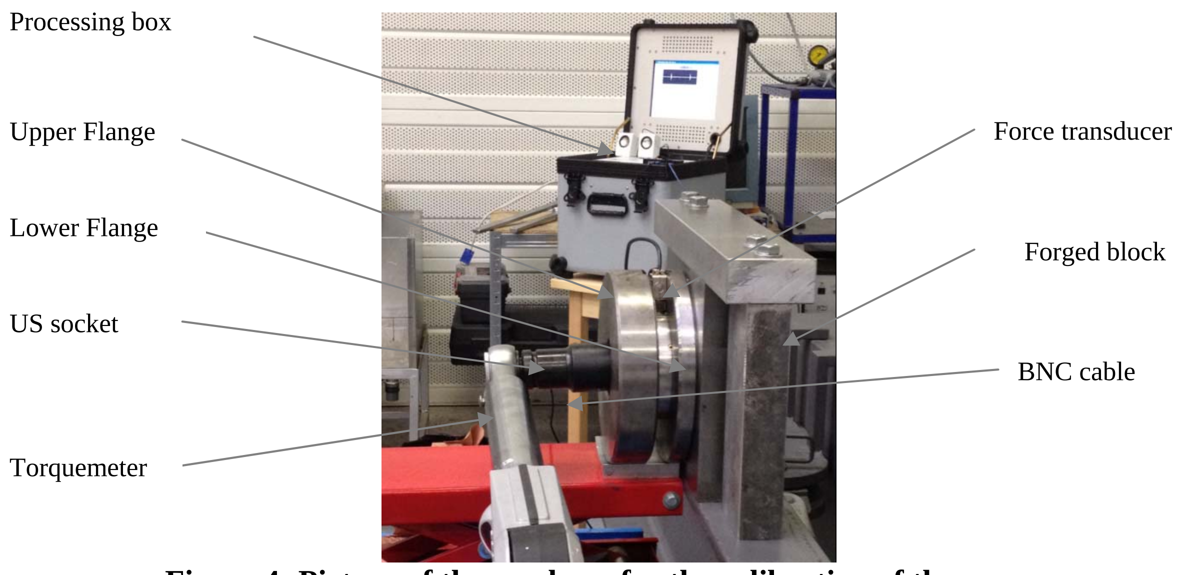


Figure 4: Picture of the mock-up for the calibration of the screws

The screw is tightened on the mock-up and for each level of force the associated travel time is measured by the US equipment and the actual applied force by the force transducer (F_{TR}).
The calibration coefficient (K) is the slope of the built curve (See fig.5).

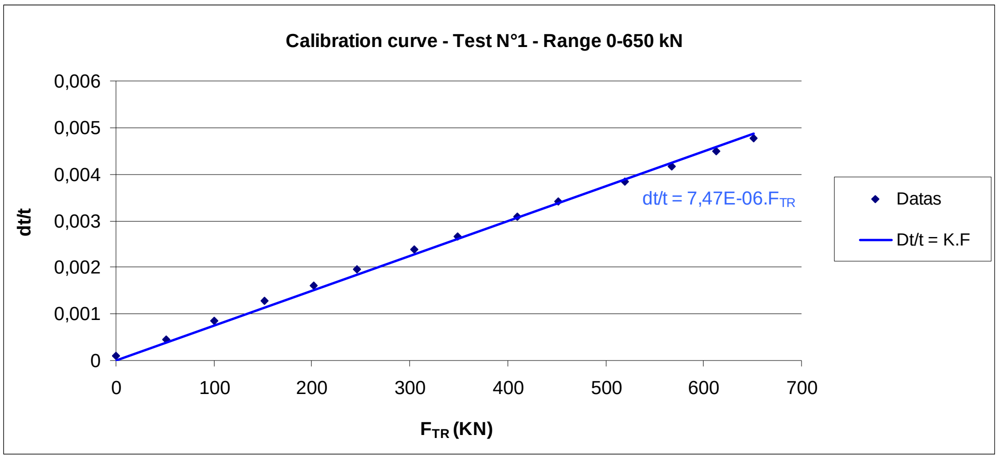


Figure 5: Example of calibration curve of a trunnion screw

Once the Calibration coefficient (K) is determined, the actual load of a screw is measured only by the US equipment using the formula: $F_{US} = \frac{1}{K} . \frac{t - t_0}{t}$ (6)

With,

- F_{US} = *Tightening force applied in the screw measured by the US equipment.*

QUALIFICATION OF THE METHOD

Within the TN®24E flask project, the new method was qualified by TN international and the TÜV Rheinland as expert of the German authority BAM to guaranty compliance with BAM standard GGR 011 <5>.
The qualification procedure was agreed and the subcontractor who develops the equipment was audited and qualified by both TNI and the German Authority.
The method and equipment are qualified in accordance with the need of the TN®24E flask project as explained in section “application for the TN®24E flask”.

DETERMINATION OF THE CALIBRATION COEFFICIENT OF A SCREW

The calibration coefficient of a screw is determined as explained in the previous section.
To see the eventual influence of some parameters on the calibration coefficient of the screws, several tests were performed with different test conditions:

- Determination of the calibration coefficient of the screw at ambient temperature by tightening
- Determination of the calibration coefficient of the screw at elevated temperature by tightening
- Determination of the calibration coefficient of the screw at ambient temperature by un-tightening

The results are shown in the fig.6 and fig.7

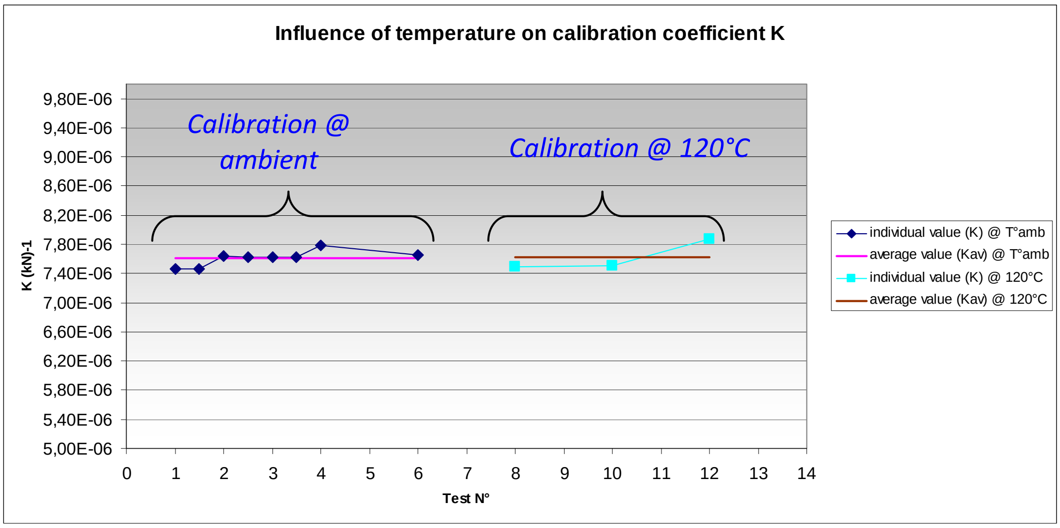


Figure 6: Influence of temperature on the calibration coefficient (K)

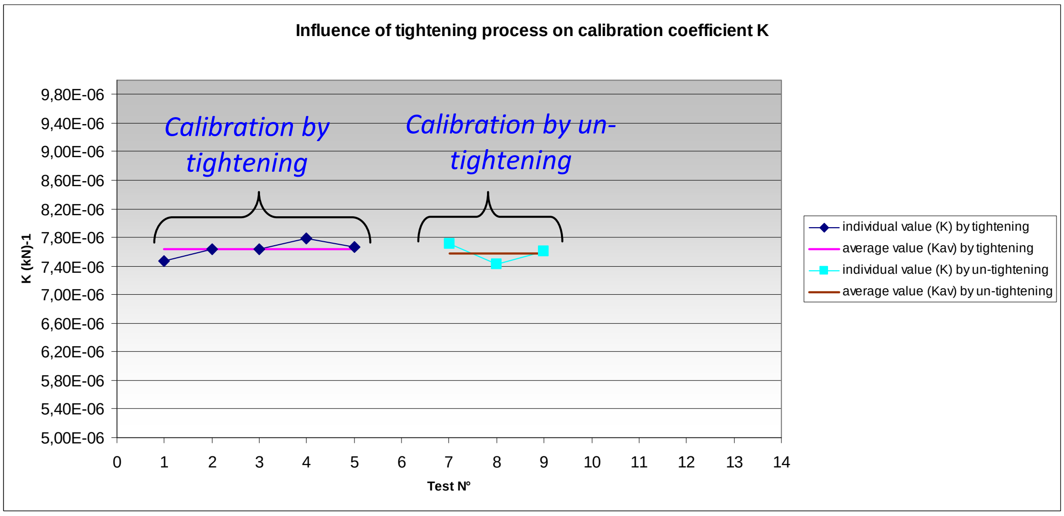


Figure 7: Influence of tightening process on the calibration coefficient (K)

- **No relevant dependency of the calibration coefficient of both the temperature and the tightening process (tightening or un-tightening) was found.**

CONTROLLED TIGHTENING OF A SCREW UNTIL A SPECIFIED FORCE

- Controlled tightening of a screw at ambient temperature

The mock-up described in fig.3 and 4 was used for this test.
The calibration coefficients of the screws were previously determined.

The screw is tightened to a specified load and the actual force is measured by both the force transducer (F_{TR} which is considered as the reference) and the US equipment (F_{US}).

Then the error of the method is calculated as following: $error(\%) = \left|\frac{F_{TR} - F_{US}}{F_{TR}}\right| \cdot 100$ (7)

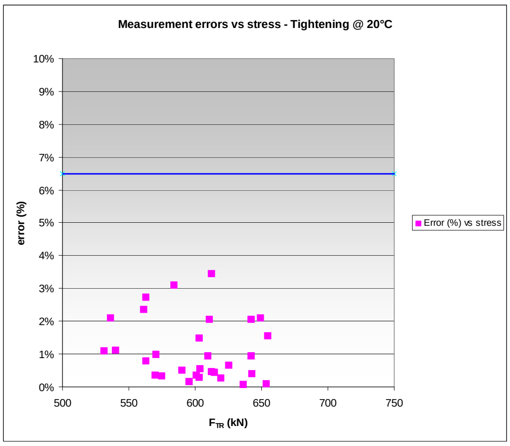


Figure 8: Tightening at ambient temperature – Error vs stress

- **As shown in the fig.8, this method enables to accurately tighten a screw up to a specified force.**

- Controlled tightening of a screw at high temperature

A heating system was added on the mock-up in order performing this test. The mock-up was heated and a gradient of temperature was created to simulate the loaded flask condition (see fig.9).
Due to the high temperature reached in the screw head, a specific coupling product had to be used to obtain a good US signal.

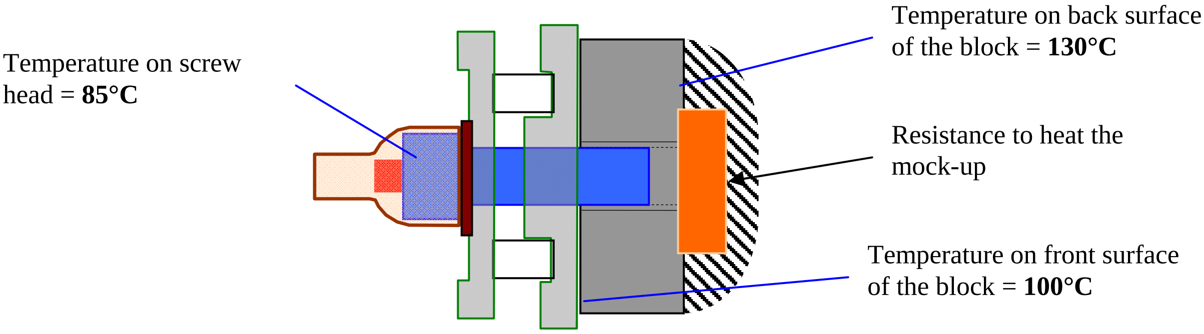


Figure 9: Description of the mock-up for the test at high temperature

Several screws were tightened after stabilisation of temperature on the mock-up until 610KN. The force was measured by both the force transducer (F_{TR}) and the US equipment (F_{US}). The error was calculated using the formula (7) and the results are shown in the fig.10.

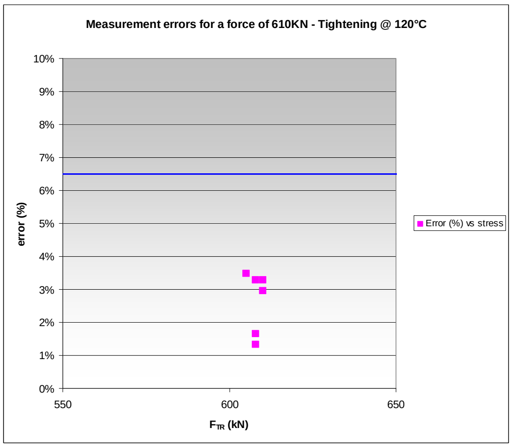


Figure 10: Tightening at high temperature – Error vs stress

➢ **The method is applicable for the tightening of screw at higher temperature or with a gradient of temperature through the screw length comparable to the flask in loaded condition. It's only necessary to check the stability of temperature during the tightening.**

CONTROL OF THE FORCE OF TIGHTENED SCREWS

- Control of the force on a already tightened screw (without un-tightening it)

The temperature has an impact on the travel time of the screw as shown in <2>.
Without taking into account the effect of the temperature, the measured force by the US equipment will be incorrect because of the temperature influence. To take into account the temperature effect on the force measurement, a specific method was developed.
The qualification test was done according to fig. 11 and the results are shown in table 1 and fig.12.

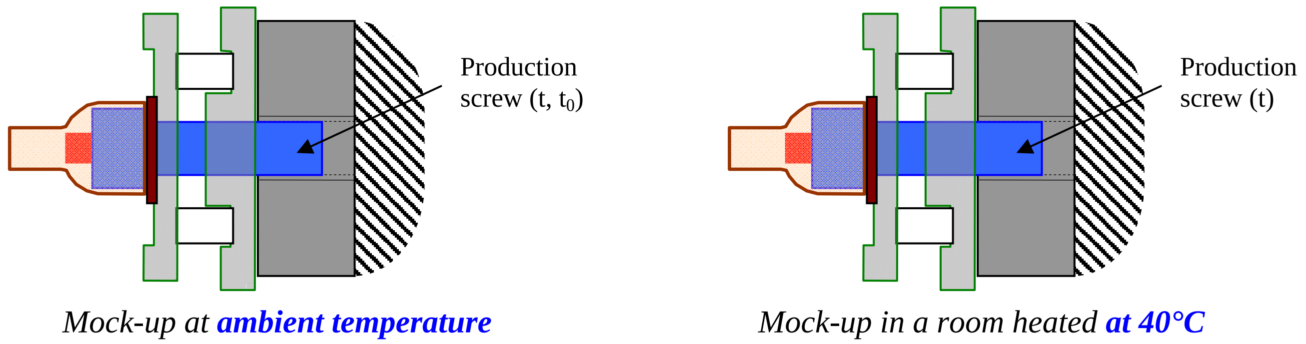


Figure 11: Configuration of the mock-up to see the influence of temperature

Table 1: Example of measurements with the influence of the temperature

	At 20°C	At 40°C	Comments
F_{TR}	604 kN	604 kN	F_{TR} is used as the reference
F_{US} without correction	610 kN	**820 kN**	
F_{US} with correction	/	**614 kN**	

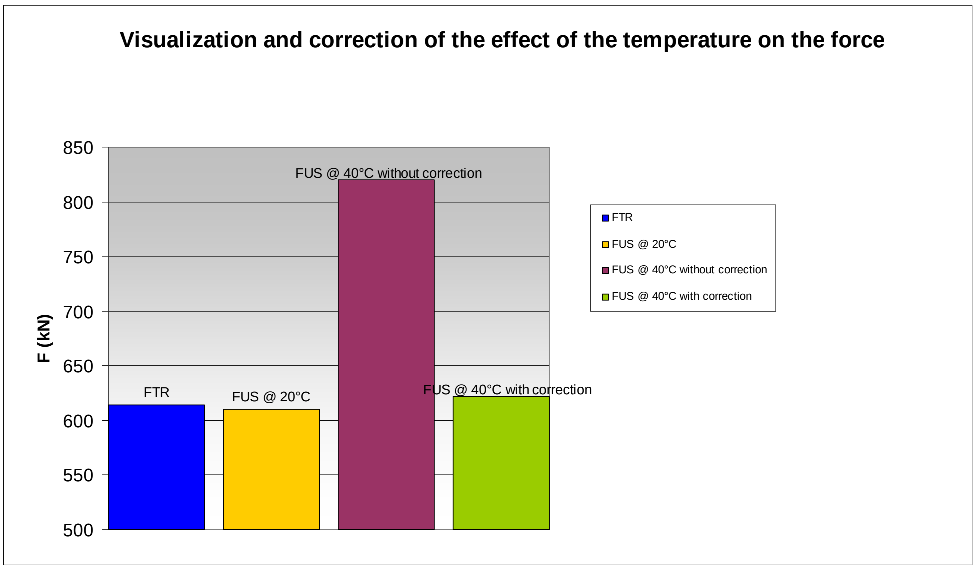


Figure 12: Visualisation of the effect of the temperature on the measurement

➢ **The method is appropriated for <u>the control of the tightening force on screw already tightened on flask</u> and is only applicable if the screw temperature is homogeneous.**

- <u>Control of the force by un-tightening the screw</u>

In case of if it is not possible to correct the temperature, the measurement of the force could be performed by un-tightening the screw.

Indeed, in this case, the initial state of the screw is “loaded screw”, the US equipment is able to measure the travel time **t** of the screw. The final state is the “un-loaded” screw, the US equipment could measure the travel time $\mathbf{t_0}$ (see fig.13).

The formula becomes: $F_{US} = \frac{1}{K} \cdot \frac{t_0 - t}{t_0}$

Initial state: Screw tightened
- Force: F (to be determined)
- Travel time t (measured by US device)

Final state: Screw fully un-tightened
- Force = 0 N
- Travel time t_0 (measured by US device)

Fig. 13: Measurement of the tightening force by un-tightening the screw

During the qualification, several screws were tightened until a force of 610KN on a mock-up at both ambient (see fig. 3) and elevated temperatures (see fig.9).
For each test, the force was measured by both the force transducer (F_{TR}) and the US equipment (F_{US}) and the error was calculated. The results are shown in fig.14.

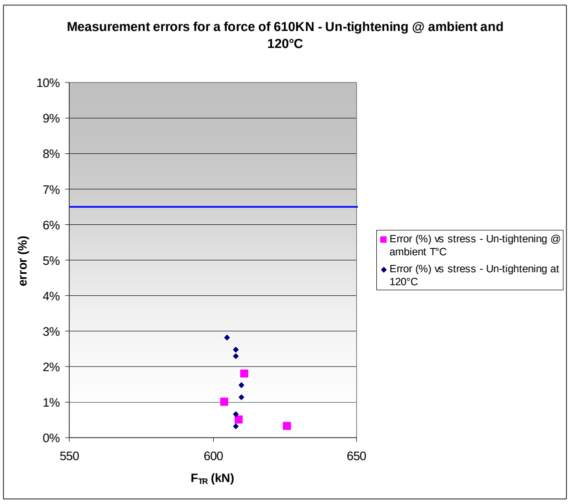


Fig. 14: Un-tightening at ambient and high temperatures – Error at a stress level of 610KN

➢ **The control of the force by un-tightening the screw prevents from the temperature effect on the travel time under the prerequisite that there is a temperature stability during the un-tightening. Furthermore, this method provides accurate results.**

APPLICATION FOR THE TN®24E FLASK

The application of this method for the flasks is summarized in the table 2.

Table 2: Application of the US stress tightening method on the TN®24E flask

	Situation	Type of test
1.1	Assembly of trunnion screw on an **un-loaded flask**	Controlled tightening of the trunnion screws up to a specified force
1.2	Control of the trunnion screws after trunnion load test / in-service inspection on an **un-loaded flask**	Control of the tightening force of the trunnion screw by un-tightening
1.3		Control of the tightening force of the trunnion screw without un-tightening
2.1	Assembly of trunnion screw on a **loaded flask**	Controlled tightening of the trunnion screws up to a specified force
2.2	Control of the trunnion screws after load test / in- service inspection on a **loaded flask**	Control of the tightening force of the trunnion screw by un-tightening

CONCLUSION

This new method enables to increase a lot the accuracy of the tightening force measurement comparing to the “standard” methods (below to 6.5% instead of 20%). Thus, it’s possible to tighten a screw to a higher force without improving the risk to damage it.
Even if there is an influence of temperature on the US, some simple methods could be used to correct this effect. This permits an easy application of this method on loaded flasks and / or in case of variation of the temperature of the shop where the flasks are stored.

Furthermore, the application of this new method doesn’t request huge investments in term of material or operator qualification.

For the TN®24E flask, the method is fully qualified and will be applied on the actual flasks.

REFERENCE

<1> EMATS for science and industry: noncontacting ultrasonic measurements – Masahiko Hiraro and Hirotsugu Ogi.

<2> Ultrasonic stress measurement with the LCR technique - Don E. Bray - 24 July 1998

<3> NTC-11-00045537 rev.00 – Qualification report for the US stress tightening system – TN International – 10/2011

<4> RAP-12-00064416 rev 00 - Qualification report for the US stress tightening system / Enlargement of the initial scope – TN International – 07/2012

<5> BAM-GGR011 – Quality assurance measures of packagings for competent authority approved package designs for the transport of radioactive materials – 06/2010

<6> KTA 3905 – Load attaching points on loads in Nuclear Power Plant – 11/2012

<7> VDI 2230 – Systematic calculation of high duty bolted joints – Joints with one cylindrical bolt 02/2003