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MASTERING REQUIREMENTS ON CONTAINMENT BOUNDARY

Hervé Ripert
Orano TN
2 rue des Hérons
78100 Montigny Le Bretonneux
France

Damien Sicard
Orano TN
2 rue des Hérons
78100 Montigny Le Bretonneux
France

Pierre Cavelius
Orano TN
2 rue des Hérons
78100 Montigny Le
Bretonneux
France

Fréderic Nicodéme
Orano TN
2 rue des Hérons
78100 Montigny Le
Bretonneux
France

Stephane Nallet
Orano TN
2 rue des Hérons
78100 Montigny Le
Bretonneux
France

ABSTRACT

For B(U)-F packages, IA~~AI~~EA 96 regulation requires no brittle fracture risk down to - 40°C for containment system and multiple high standard water barriers in order to consider water exclusion. Thick forged body with two leak tight lids are accepted as adequate by the French Authority to meet the~~o~~se requirements if sufficient margins does exist regarding brittle fracture on all their components including the bottom to shell welds. To exclude this risk for thick forged body, ferritic carbon steels dedicated to~~for~~ cryogenic application had been selected by Orano TN, with the following standard practices: a qualification of the material, a brittle fracture analysis, a qualification of the process. The qualification of the material includes the definition of the dynamic minimal toughness at -40°C with high loading rates. The obtained values for Orano TN forged steels and welds are very much higher than the one obtained with many other materials used for cask applications, such as for example ductile cast iron. The brittle fracture analysis considers the 1.4 additional minimal safety factor required by IAEA Tecdoc 717. In addition, as required by the French safety authority, the justifications deal with stress concentration areas like basket key grooves, bolts hole and any adjunction to the package (9 meters drop on the transport frame). The qualification of each manufacturer process (forged parts and weld) with an extend mechanical test program on the first part of each type of cask with the aim of detecting the weakest zone which will be used for the testing in serial production. - a volumetric ultrasonic examination with EN 10228-3 ~~a~~ quality level 3~~ of EN 10228-3~~, more stringent than the flaw size considered in the brittle fracture analysis. Furthermore, an extensive review was performed on more than 300 forged parts produced by Creusot Forges over 30 years. It showed the robustness of the manufacturing process and

helped to the continuous improvement of the state of the art in terms of quality requirements. Altogether additional safety margins are established so that Orano TN forged casks are a unique and robust solution to face future evolution of international or national requirements.

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INTRODUCTION

For B(U)-F packages, ~~A~~IAEA 96 and subsequent require the mechanical strength:

- Of the containment boundary,
- Of multiple high standard water barriers to consider water exclusion from a safety criticality point of view.

In particular, the risk of brittle Fracture down to - 40°C shall be excluded.

Thick forged body with two leak tight lids (see figure 1) are considered as adequate by the French Authority if sufficient margins does exist regarding brittle fracture on all their components including the bottom to shell welds. For non-ductile materials at -40°C in dynamic conditions (high loading rates), Orano TN corresponding justification relies on the following specific steps:

- From a design point of view, the justification and margin rely first on material selection and qualification to ensure a high dynamic toughness, and second on a safety analysis of the concerned cask components in accidental conditions of transport. For this purpose, a maximal allowable flaw size is considered taking into the performance of the manufacturing process and an the control ,
- From a manufacturing point of view, the justification and margin rely first on the manufacturer qualification regarding forged parts and welds, and second with volumetric examination performance with introduction of size limitation for discontinuities.

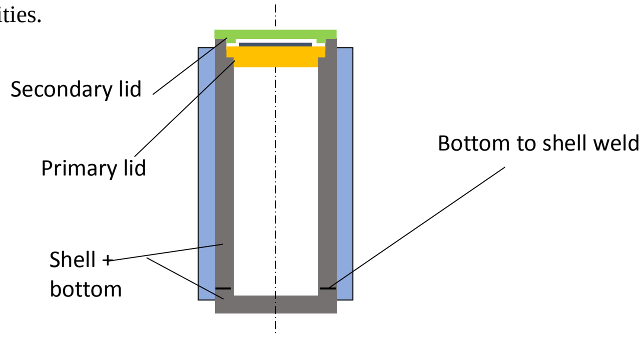


Figure 1. Containment components of a dual-purpose cask

MATERIAL SELECTION

To demonstrate that there is no risk of brittle fracture different way can be used. Selection of ductile material such as austenic stainless steel of nickel alloy is one option. For other material such as ductile cast iron, ferritic carbon steel, duplex steel or martensitic steel, the risk has to be considered and evaluated with fracture mechanic.

For its main applications, Orano TN have selected ferritic cryogenic steels such as A350 LF-5 class 2, with different nickel contents, high mechanical properties, and a good thermal conductivity compared to stainless steels.

MATERIAL QUALIFICATION

The Charpy-V test is ~~shall be considered as~~ a simple qualitative test that gives ~~only~~ an indication of the toughness of a metal. It is an inexpensive test very convenient for production test. This test is well adapted to making~~e~~ sure that the quality is reproduc~~t~~ible.

To measure the toughness of the material it is necessary to prepare costly samples with a machined notch in~~at~~ the centre which is then extended by cyclic loading up to the center of the samples (see figure 2).

The dynamic toughness Kd is calculated according to the equation below using the Jd value which represents the absorbed energy (area below the curve). It is computed according to the ASTM E 1921 standard test method assuming plane strain conditions.

$$KJ_d = \sqrt{J_d \cdot \frac{E}{1-\nu^2}}$$

E = Young modulus, ν =poison ratio = 0,3.

The tests are performed at a loading rate (dK/dt) equal to 10.000 MPa.√m / s, bounding the real loading rates of Orano TN casks in accidental conditions of transport. The adequate definition of the bounding loading rate is essential since it may increase significantly the transition temperature from ductile to brittle behavoiur.

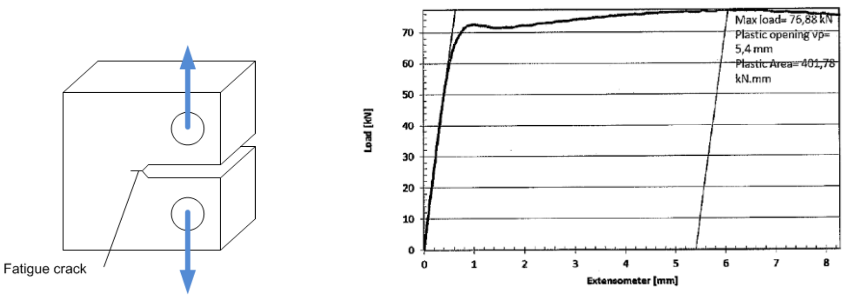


Figure 2. Toughness test sample and curve

The base material qualification is conducted~~performed~~ on a representative material with a significant number of samples in order to evaluate the dynamic toughness dispersion and to define the minimal ensured value with a high confidence level.

Tests are performed from samples extracted in   thick forged parts, in which 25 mm thick samples are machined. The sample crack front length is bounding the one corresponding to the manufacturing rejection flaw size criteria.

For the examples of A350 LF5 class 2, tests performed showed that:

- the manufacturing requirement on KCV (>140 J at -40°C) ensures a dynamic toughness ranging from 182 MPa.√m to 282 MPa.√m,
- for the welded area, both the weld material and the Heat Affected Zone exhibit high toughness values up to 190 MPa.√m.

Orano TN casks have high dynamic toughness, whatever considered forged parts or welds. They are very much higher than the one obtained with many other materials used for cask applications, such as for example ductile cast iron for which only a dynamic toughness of approximately 50 MPa.√m can be ensured.

BRITTLE FRACTURE ANALYSIS WITH ENHANCED REQUIREMENTS

When the material selected required, a brittle fracture analysis at -40°C , it is realized in 4 steps:

- dynamic calculations of the cask in accidental condition of transport using a qualified model,
- identification of the area with the highest maximal principal stress for each drop configuration,
- calculation of the maximal corresponding stress intensity factors, considering a maximal flaw size achievable by manufacturing process and consistent with NDE control equipment capabilities,
- comparison of the maximal stress intensity factors to the minimal dynamic toughness of the component, with the consideration of a 1.4 additional minimal safety factor required by IAEA Tecdoc 717.

Moreover, as required by the French safety authority, the justifications deal with stress concentration areas like basket key grooves, bolts holes (see figure 3).

In addition, dedicated brittle fracture analysis are performed to comply with French safety authority expectation on the requirement coming from IAEA concerning the behavior with adjunction to the package. Indeed, the 9 meters drop on the transport frame (figure 4) leads to different drop test results than regulatory transport tests, that may increase significantly the stress intensity factor in some areas like trunnions housing areas.

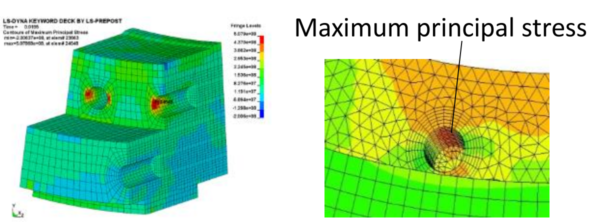


Figure 3. Stress concentration – example lid bolt holes

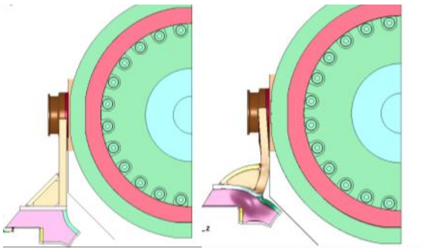


Figure 4. 9 meters drop on the transport frame

On the basis of such analysis, Orano TN casks based on thick ferritic forging containment have additional safety margins in addition to the 1.4 additional safety factor required by IAEA Tecdoc 717. For example, TN24 dual purpose casks exhibits a 2,1 minimal safety factor.

MANUFACTURERS QUALIFICATION OF FORGING PROCESS

For each new type of forging with a new supplier, a qualification test program is performed. It is an extended test program featured to :

- check the homogeneity of the properties in the forging: identification of the weakest area from mechanical and brittle fracture point of view, where serial production quality control tests will have to be performed,
- verify that the minimal dynamic toughness at -40°C is consistent with the minimal one defined during the material qualification and taken into account in the safety analysis.

This manufacturer qualification is valid as long as there is no change in major parameters of forging (manufacturing process of the ingot, ingot type, forging sequence and ratio) and heat treatment process. ~~.~~

The test program is based on at least two test rings for a large shell positioned at each extremity. The test rings are fitted with a thermal buffer or extra material so as ~~in order~~ to be representative of any section~~s~~ of the shell. If both extremities meet the expected properties, the same would be true ~~then it is the case~~ for the rest of the shell.

In each test ring, the tests are~~will be~~ performed at 3 locations: quarter thickness, mid-thickness, three quarter thickness (see figure 5). The different locations are required as there is a difference in cooling speed over the thickness during the heat treatment. The cooling speed can indeed influence the metallographic structure of the steel and the related toughness properties. For each location, tensile tests are conducted ~~performed~~ as well as Charpy impact tests. They ~~Charpy impact tests~~ are used to identify the weakest area for performing the dynamic toughness test. In many cases, the weakest area is located at mid-thickness.

The discard rate is also an important issue since there is a risk of segregation during the casting operation of an ingot or a ductile cast iron part. For large ingot the segregation of carbon or inclusions can be very detrimental to the mechanical properties. Hence, a chemical analysis and non-metallic inclusions test according to ASTM E45 at several positions ~~locations~~ is included in the qualification of the process.

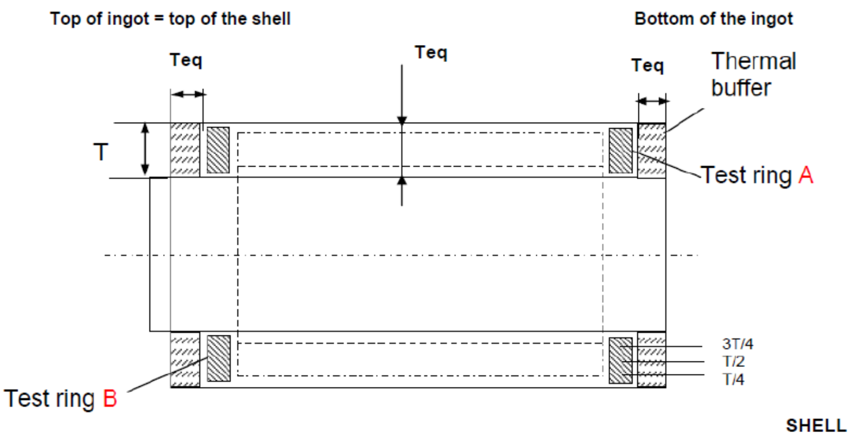


Figure 5 Location of impact test samples and toughness test samples

MANUFACTURERS QUALIFICATION OF WELDING PROCESS

To ensure adequate performance special measures are needed for the qualification of each supplier welding process. ~~Additional r~~Requirements in addition to those of ASME IX are then implemented to verify the weld properties over the full thickness. Samples are machined at different positions in the weld and in the heat affected zone. Charpy impact test samples are performed at least at the root, T/4, mid-thickness ("T/2" in Figure 6), 3 T/4, and the surface to detect the zone with the weakest area. In this latter area the following complementary tests are carried out~~done~~:

- Charpy impact tests at different temperatures to define transition curve,
- mechanical tests at -40°C,
- at least 15 dynamic toughness tests (CT25) to check the compliance with the minimum characteristics used in the brittle fracture analysis.

In addition to ASME supplementary essential variables ~~parameters~~, the following additional ones shall be considered as part of the qualification process:

- Change of welding head type
- Change of groove dimensions
- Change of position of the welding path
- Change of welding flux reference
- Change of welding material dimensions
- Electrical parameters (U and I) and welding speed outside the range used for the supplier qualification
- PWHT heat and cooling rate outside the specified maximum and minimum
- Change of PWHT holding time

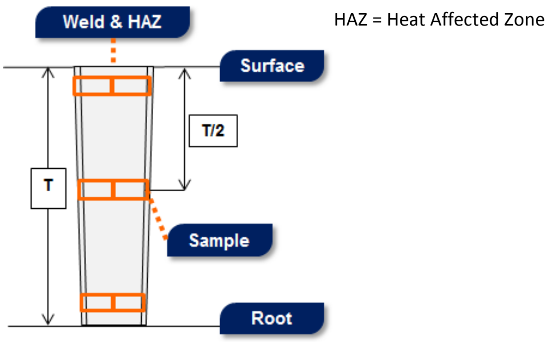


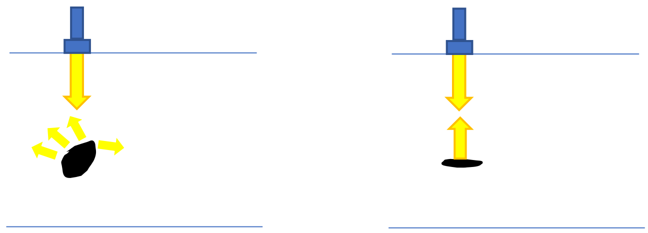
Figure 6. Location of impact test samples

VOLUMETRIC EXAMINATION

Volumetric control of 100% of the manufactured parts shall be done, to check that no flaw does exists exceeding the rejection criteria considered in the brittle fracture analysis. For forged parts, ORANO TN requires the application of the quality level 3 according to EN 10228-3 (most advanced state of the art for large forgings). It corresponds to isolated indications with a reflectivity equivalent to a flat bottom hole of 5 mm. In addition, the sensitivity is set on a flat bottom hole of 2 mm to detect and exclude potential hydrogen induced indications (hydrogen flakes).

For the selection of the non-destructive method, the type of potential defects shall be considered.

The conventional ultrasonic method is sensitive to their orientation. Such orientation shall be close to the normal of the sound beam. Containment bodies based on thick forging have the advantage of having defects with preferred orientation (see Figure 7). Due to the forging process, the potential defects in the ingots are flatten and are oriented parallel to the surface, making the control easier. Thus, the safety is improved when compared to other manufacturing process (casting for example).



Not oriented defect and sphere type defect with limited detectability

Oriented forging defects with high reflectivity of ultrasonic beam

Figure 7. Impact of material manufacturing process on ultrasonic test detectability

For the bottom to shell weld, the detection of non-volumetric indications such as cracks, lack of fusion is essential because~~since~~ they may be very detrimental discontinuities. In the case of a narrow gap weld, foreseen discontinuities, ~~like~~ for example lack of fusion parallel to the weld seam can be detected thanks to an additional scanning of the bottom (figure 8). In such~~those~~ thick welds, the strategy of control defined by ASME V A~~a~~rticle 4 may not be sufficient since. ~~it has to take into account~~ T~~t~~he specific geometry of the weld must be taken into account. This additional scanning offers a very good reflectivity of the signal and an~~the~~ adequate detectability.

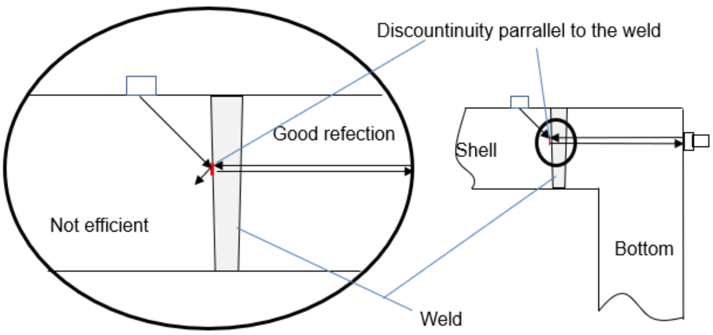


Figure 8. Weld UT inspection

In some designs, Pulse echo is not convenient. For example, in the case of a draining orifice, it may not be possible to reach the weld with the ultrasonic beam (see figure 9). In such a situation, the TOFD (Time-Off-Flight Diffraction technology) is used. This technology is also very efficient for the detection of non-volumetric indications. The a~~A~~cceptance level can be set to indications of less than 3 mm in height for surface breaking defect with maximum length of 12 mm.

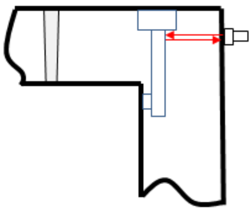


Figure 9 Design with draining orifice

PRODUCTION RELIABILITY: FEEDBACK FROM THE ANALYSIS OF 300 FORGING FILES

Following the documentation anomalies (mainly relied to reporting of the manufacturing process) found on some boilers forged parts produced by Creusot Forge, all the files of the nuclear cask forging parts ever produced by Creusot Forge for Orano TN were reviewed and checked under the French Authority control. More than 300 parts were 100% checked. The conclusion was that all casks are 100% consistent with all safety criteria. The feedback of such review was further used as recommendations in forging specification, thus continuously improving the mastering of quality for such component.

CONCLUSION

Orano TN casks with containment and water barriers based on thick welded forging is a robust and proven solution. The designs include significant margin in addition to the safety coefficient 1.4 requested by AIAEA Tecdoc 717 and allows containment with thick forged steels and welds to meet the highest standards in comparison to the ones obtained with many other materials used for cask applications, It is a very efficient solution to face future evolution of regulation requirements.

ACKNOWLEDGMENTS

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REFERENCES

EN 10228-3 Non-destructive testing of steel forgings — Part 3 : Ultrasonic testing of ferritic or martensitic steel forgings

ASME IX Qualification Standard for Welding and Brazing Procedures, Welders, Brazers, and Welding and Brazing Operators

AIEA Tecdoc 717