ENERCON Excellence—Every project. Every day	CALCULATION COVER SHEET	CALC. NO. RTL-001-CALC-TH-0102 REV. 6 PAGE NO. 1 of 9

Title:	RT-100 Cask Maximum Normal Operating Pressure Calculation	**Client:**	Robatel Technologies, LLC
		Project:	Robatel002

Item	Cover Sheet Items	Yes	No
1	Does this calculation contain any open assumptions that require confirmation? (If **YES**, Identify the assumptions) ____	☐	☒
2	Does this calculation serve as an "Alternate Calculation"? (If **YES**, Identify the design verified calculation.) **Design Verified Calculation No.** ____	☐	☒
3	Does this calculation Supersede an existing Calculation? (If **YES**, identify the superseded calculation.) **Superseded Calculation No.** ____	☐	☒

Scope of Revision:

Revision 6 is being made to update the revision level of several reference calculations and to clarify the assumption of oxygen production due to radiolysis of water.

Revision Impact on Results:

N/A

Study Calculation ☐ **Final Calculation** ☒

Safety-Related ☒ **Non-Safety Related** ☐

(Print Name and Sign)

Originator: David Hartmangruber	[signature]	**Date: 01/03/2014**
Design Verifier: Curt Lindner	[signature]	**Date: 01/03/2014**
Approver: Nand Lambha	[signature]	**Date: 01/03/2014**

CALCULATION REVISION STATUS

REVISION	DATE	DESCRIPTION
0	Sept 12, 2012	Initial Issue
1	Oct. 5, 2012	Update References and Editorial Changes
2	Nov. 29, 2012	Editorial Changes and Attach Reference Pages
3	Aug. 28, 2013	Updated temperature reference per new NCT temperatures
4	Sep. 4, 2013	Incorporated customer comments
5	Sep. 12, 2013	Revised calculation revision levels
6	Jan. 3, 2014	Updated revision numbering of references.

PAGE REVISION STATUS

PAGE NO.	REVISION	PAGE NO.	REVISION
All	6		

APPENDIX REVISION STATUS

APPENDIX NO.	PAGE NO.	REVISION NO.	APPENDIX NO.	PAGE NO.	REVISION NO.
1	All	2			

Calculation Design Verification Plan:

Calculation to be reviewed for correctness of inputs, design criteria, analytical methods, acceptance criteria and numerical accuracy.

Stated objectives and conclusions shall be confirmed to be reasonable and valid.

Any assumptions shall be clearly documented and confirmed to be appropriate and verified based on sound engineering principles and practices.

(Print Name and Sign for Approval – mark "N/A" if not required)

Approver: Nand Lambha	**Date: 01/03/2014**

Calculation Design Verification Summary:

Calculation has been designated as **Safety Related** as noted on the cover sheet.

Calculation has been verified to be mathematically correct and performed in accordance with appropriate design inputs, assumptions, analytical methods, design criteria and acceptance criteria.

The conclusions developed in the calculation are reasonable, valid and consistent with the purpose and scope.

Assumptions are appropriate and correct.

Based On The Above Summary, The Calculation Is Determined To Be Acceptable.

(Print Name and Sign)

Design Verifier: Curt Lindner	**Date: 01/03/2014**
Others:	**Date:**

ENERCON Excellence—Every project. Every day	CALCULATION DESIGN VERIFICATION CHECKLIST	CALC. NO.	RTL-001-CALC-TH-0102
		REV.	6
		PAGE NO.	

Item	CHECKLIST ITEMS	Yes	No	N/A
1	**Design Inputs** - Were the design inputs correctly selected, referenced (latest revision), consistent with the design basis, and incorporated in the calculation?	X		
2	**Assumptions** - Were the assumptions reasonable and adequately described, justified and/or verified, and documented?	X		
3	**Quality Assurance** - Were the appropriate QA classification and requirements assigned to the calculation?	X		
4	**Codes, Standards, and Regulatory Requirements** - Were the applicable codes, standards, and regulatory requirements, including issue and addenda, properly identified and their requirements satisfied?	X		
5	**Construction and Operating Experience** - Have applicable construction and operating experience been considered?			X
6	**Interfaces** - Have the design-interface requirements been satisfied, including interactions with other calculations?	X		
7	**Methods** - Was the calculation methodology appropriate and properly applied to satisfy the calculation objective?	X		
8	**Design Outputs** - Was the conclusion of the calculation clearly stated, did it correspond directly with the objectives, and are the results reasonable compared to the inputs?	X		
9	**Radiation Exposure** - Has the calculation properly considered radiation exposure to the public and plant personnel?			X
10	**Acceptance Criteria** - Are the acceptance criteria incorporated in the calculation sufficient to allow verification that the design requirements have been satisfactorily accomplished?	X		
11	**Computer Software**- Is a computer program or software used, and if so, are the requirements of CSP 3.02 met?			X

COMMENTS

(Print Name and Sign)	
Design Verifier: **Curt Lindner** [signature]	**Date:** **01/03/2014**
Others:	**Date:**

Table of Contents

1.0 PURPOSE AND SCOPE

Robatel Technologies is designing the RT-100 transport cask to transport radioactive waste in the form of dewatered resins and filters. The RT-100 transport cask is required to meet the requirements of 10 CFR Part 71 (Ref. 3.1). The purpose of this calculation is to calculate the cask cavity Maximum Normal Operating Pressure (MNOP) under the Normal Conditions of Transport (NCT).

2.0 SUMMARY OF RESULTS AND CONCLUSIONS

A pressure of 342.7 kPa [49.7 psia] is recommended for use in the cask analysis under normal conditions of transport (NCT) requiring MNOP.

3.0 REFERENCES

3.1 Nuclear Regulatory Commission, 10 CFR Part 71, "Packaging and Transportation of Radioactive Material"

3.2 J. Chang, P. Lien, and M. Waters, Evaluation of Hydrogen Generation and Maximum Normal Operating Pressure for Waste Transportation Packages, WM2011 Conference, Feb 27 – Mar 3, 2011, Phoenix, AZ

3.3 ENERCON Calculation RTL-001-CALC-TH-0201 Rev. 6, "RT-100 Cask Thermal Evaluation"

3.4 Fundamentals of Engineering Thermodynamics, 5th Edition, M. Moran and H. Shapiro

3.5 Fundamental of Fluid Mechanics, 4th Edition, B. Munson, D. Young and T. Okiishi

3.6 ENERCON Calculation RTL-001-CALC-SH-0301 Rev. 4, "Application of RT-100 Loading Table in Shielding Evaluations"

4.0 ASSUMPTIONS

(1) Ideal gas law is used to calculate the cask cavity pressure at a given temperature. The content inside the cask is dewatered resins and filters, water amount is very limited. Air occupies the cask cavity. The gas within the cask, a mixture of air, water, oxygen and hydrogen generated through radiolytic decomposition of the water residual, behaves as an ideal gas.

(2) The cask at the time of loading has an internal pressure equal to ambient pressure, which is assumed to be 1 atm absolute (101.35 kPa, 14.7 psia) at 21.1 °C (70 °F, 294.25 K).

(3) As required by the Reference 3.6, the user must ensure that the hydrogen generation will not exceed 5% by volume.

There are no unverified assumptions in this calculation. Other design assumptions used, if any, will be noted and referenced as needed in the body of the calculation.

5.0 DESIGN INPUTS

5.1 Temperature

Initial temperature of the gas in the cask = 21.1 °C (See Section 4.0)
Final temperature of the gas = Maximum internal cask temperature (Ref. 3.3)
= 80 °C [353.15 K, 176 °F] (Upper Bound)*
= -29 °C [244.15 K, -20.2 °F] (Lower Bound)

* 80 °C [353.15 K, 176 °F] conservatively bounds the 73.1 °C [346.25 K, 163.6 °F] maximum internal cask temperature determined in Ref. 3.3 by nodal averaging of the inner cavity surface temperatures for Normal Conditions of Transport.

5.2 Pressure

Initial pressure of the gas in the cask = 1 atm abs. [14.7 psia, 101.35 kPa] (See Section 4.0)

6.0 METHODOLOGY

To determine the MNOP, the temperature of the gas mixture within the cask is evaluated. The maximum temperature of the cask cavity under normal condition is bounded by upper and lower temperature range of 80 °C to -29 °C (See Section 5.1).
The maximum pressure is the sum of three components:

1. the pressure due to air in the cavity;
2. the pressure due to water vapor in the cask; and
3. the pressure due to the hydrogen and oxygen gases generated by radiolysis.

The restriction of the contents to inorganic materials eliminates the potential for gas generation due to thermal degradation or biological activity. Thus, these gas sources are not considered in the evaluation.
Per the ideal gas law, air pressure and water vapor pressure are directly proportional to the temperature and with increase in temperature, the total pressure also increases. Thus, upper bound temperature will result in a higher maximum normal operating pressure for the cask compared to lower bound. The gas mixture in the cavity is conservatively assumed to be 80 °C (See Section 5.1).

7.0 CALCULATIONS

7.1 Pressure Due to Initial Air in the Cavity

Per the ideal gas law, the increased partial pressure of the air (P_{air}) initially sealed in the fixed volume of the cask at the ambient temperature as it is heated to 80 °C is:

P1xT2 = P2xT1 (Ref. 3.4)

P_{air} = 101.35 kPa[(353.15 K) / (294.25 K)] = 121.64 kPa (17.64 psia)

7.2 Pressure Due to Water Vapor in the Cask

The cask cavity is assumed to contain a small amount of water. Thus, conservatively assuming a condensing surface temperature of 80 °C, the water vapor pressure, P_{wv}, at this temperature is 47.34 kPa [6.87 psia] (Ref. 3.5, Table B.2 on page 831).

Adding the water vapor pressure at 80 °C to the partial pressure of the air in the sealed cask at this temperature gives:

Pressure $P_2 = P_{air} + P_{wv}$ = 121.64 + 47.34 = 169.0 kPa [24.51 psia]

7.3 Pressure Due to Generation of Gas

Solid inorganic materials have a G value of zero, i.e., solid inorganic materials do not generate hydrogen or other gases through radiolysis. Solidified or dewatered material may contain some water and, if the cask is loaded underwater, a small amount of water may remain in the cavity after draining. The radiolytic generation of gases is limited to the radiolysis of this residual water. Hydrogen and oxygen may be produced in the cask by radiolytic decomposition of residual water in the cask contents. The amount of hydrogen generated in the cask cavity must not be greater than 5% by volume for the contents that include water (Ref. 3.6). Hence, the cask atmosphere is assumed to contain five volume percent of hydrogen (H_2) gas due to radiolysis of the water. To be conservative in the gas pressure calculations, the oxygen (O_2) is assumed to be released into the cask atmosphere. By stoichiometry of the water molecule (H_2O), the cask atmosphere will also contain 2.5 vol. % oxygen (O_2) gas generated by radiolysis. Noting that partial pressures in an ideal gas mixture are additive and behave the same as ideal gas volume fraction or mole fractions, the partial pressure of hydrogen is described by the following equation:

$$P_{H2} = 0.05\ P_{pt}$$

Where, $P_{pt} = P_{air} + P_{wv} + P_{H2} + P_{O2}$

Combining $P_{air} + P_{wv} = P_2$ per Section 7.2, and noting that $P_{O2} = 0.5 \times P_{H2}$.

$P_{H2} = 0.05 \times (P_2 + 1.5\ P_{H2})$

Solving the equation explicitly for P_{H2} gives:

$P_{H2} = [0.05\ P_2] / [1 - 0.05\ (1.5)]$

$= [0.05 * 169.0\ kPa] / [1 - 0.05\ (1.5)]$

$= 9.14\ kPa\ [1.32\ psia]$

7.4 Total Pressure

Based on the stoichiometric relationship between hydrogen and oxygen liberated by radiolysis of water, and again combining the pressure of the initially sealed air and water vapor as P_2, the total pressure in the cask at 80 °C is:

$P_{Total} = P_2 + 1.5\ P_{H2}$

$= 169.0\ kPa + 1.5 * 9.14\ kPa$

$= 182.71kPa\ [26.5\ psia]$

The MNOP value is conservatively set at 342.7 kPa [49.7 psia] for use in the cask analysis under normal conditions of transport (NCT).

Appendix 1—Water Vapor Pressure Reference

Appendix 1
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Fourth Edition

Fundamentals of Fluid Mechanics

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■ **TABLE B.1**

Physical Properties of Water (BG Units)[a]

Temperature (°F)	Density, ρ (slugs/ft³)	Specific Weight[b], γ (lb/ft³)	Dynamic Viscosity, μ (lb·s/ft²)	Kinematic Viscosity, ν (ft²/s)	Surface Tension[c], σ (lb/ft)	Vapor Pressure, p_v [lb/in.²(abs)]	Speed of Sound[d], c (ft/s)
32	1.940	62.42	3.732 E − 5	1.924 E − 5	5.18 E − 3	8.854 E − 2	4603
40	1.940	62.43	3.228 E − 5	1.664 E − 5	5.13 E − 3	1.217 E − 1	4672
50	1.940	62.41	2.730 E − 5	1.407 E − 5	5.09 E − 3	1.781 E − 1	4748
60	1.938	62.37	2.344 E − 5	1.210 E − 5	5.03 E − 3	2.563 E − 1	4814
70	1.936	62.30	2.037 E − 5	1.052 E − 5	4.97 E − 3	3.631 E − 1	4871
80	1.934	62.22	1.791 E − 5	9.262 E − 6	4.91 E − 3	5.069 E − 1	4819
90	1.931	62.11	1.500 E − 5	8.233 E − 6	4.86 E − 3	6.979 E − 1	4960
100	1.927	62.00	1.423 E − 5	7.383 E − 6	4.79 E − 3	9.493 E − 1	4995
120	1.918	61.71	1.164 E − 5	6.067 E − 6	4.67 E − 3	1.692 E + 0	5049
140	1.908	61.38	9.743 E − 6	5.106 E − 6	4.53 E − 3	2.888 E + 0	5091
160	1.896	61.00	8.315 E − 6	4.385 E − 6	4.40 E − 3	4.736 E + 0	5101
180	1.883	60.58	7.207 E − 6	3.827 E − 6	4.26 E − 3	7.507 E + 0	5195
200	1.869	60.12	6.342 E − 6	3.393 E − 6	4.12 E − 3	1.152 E + 1	5089
212	1.860	59.83	5.886 E − 6	3.165 E − 6	4.04 E − 3	1.469 E + 1	5062

[a] Based on data from *Handbook of Chemistry and Physics*, 69th Ed., CRC Press, 1988. Where necessary, values obtained by interpolation.
[b] Density and specific weight are related through the equation $\gamma = \rho g$. For this table, $g = 32.174$ ft/s².
[c] In contact with air.
[d] From R. D. Blevins, *Applied Fluid Dynamics Handbook*, Van Nostrand Reinhold Co., Inc., New York, 1984.

■ **TABLE B.2**

Physical Properties of Water (SI Units)[a]

Temperature (°C)	Density, ρ (kg/m³)	Specific Weight[b], γ (kN/m³)	Dynamic Viscosity, μ (N·s/m²)	Kinematic Viscosity, ν (m²/s)	Surface Tension[c], σ (N/m)	Vapor Pressure, p_v [N/m²(abs)]	Speed of Sound[d], c (m/s)
0	999.9	9.806	1.787 E − 3	1.787 E − 6	7.56 E − 2	6.105 E + 2	1403
5	1000.0	9.807	1.519 E − 3	1.519 E − 6	7.49 E − 2	8.722 E + 2	1427
10	999.7	9.804	1.307 E − 3	1.307 E − 6	7.42 E − 2	1.228 E + 3	1447
20	998.2	9.789	1.002 E − 3	1.004 E − 6	7.28 E − 2	2.338 E + 3	1481
30	995.7	9.765	7.975 E − 4	8.009 E − 7	7.12 E − 2	4.243 E + 3	1507
40	992.2	9.731	6.529 E − 4	6.580 E − 7	6.96 E − 2	7.376 E + 3	1526
50	988.1	9.690	5.468 E − 4	5.534 E − 7	6.79 E − 2	1.233 E + 4	1541
60	983.2	9.642	4.665 E − 4	4.745 E − 7	6.62 E − 2	1.992 E + 4	1552
70	977.8	9.589	4.042 E − 4	4.134 E − 7	6.44 E − 2	3.116 E + 4	1555
➡ 80	971.8	9.530	3.547 E − 4	3.650 E − 7	6.26 E − 2	4.734 E + 4	1555
90	965.3	9.467	3.147 E − 4	3.260 E − 7	6.08 E − 2	7.010 E + 4	1550
100	958.4	9.399	2.818 E − 4	2.940 E − 7	5.89 E − 2	1.013 E + 5	1543

[a] Based on data from *Handbook of Chemistry and Physics*, 69th Ed., CRC Press, 1988.
[b] Density and specific weight are related through the equation $\gamma = \rho g$. For this table, $g = 9.807$ m/s².
[c] In contact with air.
[d] From R. D. Blevins, *Applied Fluid Dynamics Handbook*, Van Nostrand Reinhold Co., Inc., New York, 1984.