ENERCON Excellence—Every project. Every day	CALCULATION COVER SHEET	CALC. NO. RTL-001-CALC-TH-0202 REV. 6 PAGE NO. 1 of 9

Title:	RT-100 Cask Hypothetical Accident Condition Maximum 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 (If **YES**, identify the superseded calculation.) **Superseded Calculation No.** ______	☐	☒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	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	Updated referenced calculations revision level
6	Jan. 3, 2014	Updated referenced calculations revision level.

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			

ENERCON Excellence—Every project. Every day.	CALCULATION DESIGN VERIFICATION PLAN AND SUMMARY SHEET	CALC. NO. RTL-001-CALC-TH-0202 REV. 6 PAGE NO. 3 of 9

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-0202
		REV.	6
		PAGE NO.	4 of 9

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 pressure under the Hypothetical Accident Condition (HAC).

2.0 SUMMARY OF RESULTS AND CONCLUSIONS

A pressure 689.4 kPa [100 psia] is recommended for subsequent HAC evaluations requiring maximum internal pressure.

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 Crane Technical Paper 410 – Flow of fluids, 2001

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 = Average internal cask temperature under HAC
= 137 °C [410.15 K, 278.6 °F] (Ref. 3.3)

Conservatively use 150 °C [423.15 K, 302 °F] (Upper Bound)*

* 150 °C [423.15 K, 302 °F] conservatively bounds the 108 °C [381.15 K, 226 °F] maximum internal cask temperature determined in Ref. 3.3 by nodal averaging of the maximum inner cavity surface temperatures for Hypothetical Accident Conditions.

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 maximum pressure, the temperature of the gas mixture within the cask is evaluated. The maximum temperature of the cask cavity under HAC is bounded by 150 °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.

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 150 °C is:
P1xT2 = P2xT1 (Ref. 3.4)
P_{air} = 101.35 kPa[(423.15 K) / (294.25 K)] = 145.8 kPa (21.15 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 150 °C, the water vapor pressure, P_{wv}, at this temperature is 475.8 kPa [69 psia] (Ref. 3.4, Appendix Table A-2 on page 761; see Appendix 1 for excerpt of the reference).

Adding the water vapor pressure at 150 °C to the partial pressure of the air in the sealed cask at this temperature gives:
Pressure $P_2 = P_{air} + P_{wv}$ = 145.8 + 475.8 = 621.6 kPa [90.16 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 $P_{O2} = 0.5 \text{ x } P_{H2}$.

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

Solving the equation explicitly for P_{H2} gives:

P_{H2} = [0.05 P_2] / [1 – 0.05 (1.5)]
= [0.05 * 621.6 kPa] / [1 – 0.05 (1.5)]
= 33.6 kPa [4.87 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 150 °C is:

P_{Total} = $P_2 + 1.5\ P_{H2}$
= 621.6 kPa + 1.5 * 33.6 kPa
= 672 kPa [97.47 psia]

The maximum pressure is 672 kPa [97.47 psia] under hypothetical accident condition. Conservatively consider 689.4 kPa [100 psia] as the maximum pressure under hypothetical accident conditions for subsequent analyses.

Appendix 1—Water Vapor Pressure Reference

5th Edition

Fundamentals of Engineering Thermodynamics

Michael J. Moran

The Ohio State University

Howard N. Shapiro

Iowa State University of Science and Technology

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Fundamentals of engineering thermodynamics/Michael J. Moran, Howard N. Shapiro.—5th edition.

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TABLE A-2 Properties of Saturated Water (Liquid–Vapor): Temperature Table

		Specific Volume m³/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Temp. °C	Press. bar	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Temp. °C
.01	0.00611	1.0002	206.136	0.00	2375.3	0.01	2501.3	2501.4	0.0000	9.1562	.01
4	0.00813	1.0001	157.232	16.77	2380.9	16.78	2491.9	2508.7	0.0610	9.0514	4
5	0.00872	1.0001	147.120	20.97	2382.3	20.98	2489.6	2510.6	0.0761	9.0257	5
6	0.00935	1.0001	137.734	25.19	2383.6	25.20	2487.2	2512.4	0.0912	9.0003	6
8	0.01072	1.0002	120.917	33.59	2386.4	33.60	2482.5	2516.1	0.1212	8.9501	8
10	0.01228	1.0004	106.379	42.00	2389.2	42.01	2477.7	2519.8	0.1510	8.9008	10
11	0.01312	1.0004	99.857	46.20	2390.5	46.20	2475.4	2521.6	0.1658	8.8765	11
12	0.01402	1.0005	93.784	50.41	2391.9	50.41	2473.0	2523.4	0.1806	8.8524	12
13	0.01497	1.0007	88.124	54.60	2393.3	54.60	2470.7	2525.3	0.1953	8.8285	13
14	0.01598	1.0008	82.848	58.79	2394.7	58.80	2468.3	2527.1	0.2099	8.8048	14
15	0.01705	1.0009	77.926	62.99	2396.1	62.99	2465.9	2528.9	0.2245	8.7814	15
16	0.01818	1.0011	73.333	67.18	2397.4	67.19	2463.6	2530.8	0.2390	8.7582	16
17	0.01938	1.0012	69.044	71.38	2398.8	71.38	2461.2	2532.6	0.2535	8.7351	17
18	0.02064	1.0014	65.038	75.57	2400.2	75.58	2458.8	2534.4	0.2679	8.7123	18
19	0.02198	1.0016	61.293	79.76	2401.6	79.77	2456.5	2536.2	0.2823	8.6897	19
20	0.02339	1.0018	57.791	83.95	2402.9	83.96	2454.1	2538.1	0.2966	8.6672	20
21	0.02487	1.0020	54.514	88.14	2404.3	88.14	2451.8	2539.9	0.3109	8.6450	21
22	0.02645	1.0022	51.447	92.32	2405.7	92.33	2449.4	2541.7	0.3251	8.6229	22
23	0.02810	1.0024	48.574	96.51	2407.0	96.52	2447.0	2543.5	0.3393	8.6011	23
24	0.02985	1.0027	45.883	100.70	2408.4	100.70	2444.7	2545.4	0.3534	8.5794	24
25	0.03169	1.0029	43.360	104.88	2409.8	104.89	2442.3	2547.2	0.3674	8.5580	25
26	0.03363	1.0032	40.994	109.06	2411.1	109.07	2439.9	2549.0	0.3814	8.5367	26
27	0.03567	1.0035	38.774	113.25	2412.5	113.25	2437.6	2550.8	0.3954	8.5156	27
28	0.03782	1.0037	36.690	117.42	2413.9	117.43	2435.2	2552.6	0.4093	8.4946	28
29	0.04008	1.0040	34.733	121.60	2415.2	121.61	2432.8	2554.5	0.4231	8.4739	29
30	0.04246	1.0043	32.894	125.78	2416.6	125.79	2430.5	2556.3	0.4369	8.4533	30
31	0.04496	1.0046	31.165	129.96	2418.0	129.97	2428.1	2558.1	0.4507	8.4329	31
32	0.04759	1.0050	29.540	134.14	2419.3	134.15	2425.7	2559.9	0.4644	8.4127	32
33	0.05034	1.0053	28.011	138.32	2420.7	138.33	2423.4	2561.7	0.4781	8.3927	33
34	0.05324	1.0056	26.571	142.50	2422.0	142.50	2421.0	2563.5	0.4917	8.3728	34
35	0.05628	1.0060	25.216	146.67	2423.4	146.68	2418.6	2565.3	0.5053	8.3531	35
36	0.05947	1.0063	23.940	150.85	2424.7	150.86	2416.2	2567.1	0.5188	8.3336	36
38	0.06632	1.0071	21.602	159.20	2427.4	159.21	2411.5	2570.7	0.5458	8.2950	38
40	0.07384	1.0078	19.523	167.56	2430.1	167.57	2406.7	2574.3	0.5725	8.2570	40
45	0.09593	1.0099	15.258	188.44	2436.8	188.45	2394.8	2583.2	0.6387	8.1648	45

TABLE A-2 *(Continued)*

Temp. °C	Press. bar	Specific Volume m³/kg Sat. Liquid $v_f \times 10^3$	Specific Volume Sat. Vapor v_g	Internal Energy kJ/kg Sat. Liquid u_f	Internal Energy Sat. Vapor u_g	Enthalpy kJ/kg Sat. Liquid h_f	Enthalpy Evap. h_{fg}	Enthalpy Sat. Vapor h_g	Entropy kJ/kg · K Sat. Liquid s_f	Entropy Sat. Vapor s_g	Temp. °C
50	.1235	1.0121	12.032	209.32	2443.5	209.33	2382.7	2592.1	.7038	8.0763	50
55	.1576	1.0146	9.568	230.21	2450.1	230.23	2370.7	2600.9	.7679	7.9913	55
60	.1994	1.0172	7.671	251.11	2456.6	251.13	2358.5	2609.6	.8312	7.9096	60
65	.2503	1.0199	6.197	272.02	2463.1	272.06	2346.2	2618.3	.8935	7.8310	65
70	.3119	1.0228	5.042	292.95	2469.6	292.98	2333.8	2626.8	.9549	7.7553	70
75	.3858	1.0259	4.131	313.90	2475.9	313.93	2321.4	2635.3	1.0155	7.6824	75
80	.4739	1.0291	3.407	334.86	2482.2	334.91	2308.8	2643.7	1.0753	7.6122	80
85	.5783	1.0325	2.828	355.84	2488.4	355.90	2296.0	2651.9	1.1343	7.5445	85
90	.7014	1.0360	2.361	376.85	2494.5	376.92	2283.2	2660.1	1.1925	7.4791	90
95	.8455	1.0397	1.982	397.88	2500.6	397.96	2270.2	2668.1	1.2500	7.4159	95
100	1.014	1.0435	1.673	418.94	2506.5	419.04	2257.0	2676.1	1.3069	7.3549	100
110	1.433	1.0516	1.210	461.14	2518.1	461.30	2230.2	2691.5	1.4185	7.2387	110
120	1.985	1.0603	0.8919	503.50	2529.3	503.71	2202.6	2706.3	1.5276	7.1296	120
130	2.701	1.0697	0.6685	546.02	2539.9	546.31	2174.2	2720.5	1.6344	7.0269	130
140	3.613	1.0797	0.5089	588.74	2550.0	589.13	2144.7	2733.9	1.7391	6.9299	140
150	4.758	1.0905	0.3928	631.68	2559.5	632.20	2114.3	2746.5	1.8418	6.8379	150
160	6.178	1.1020	0.3071	674.86	2568.4	675.55	2082.6	2758.1	1.9427	6.7502	160
170	7.917	1.1143	0.2428	718.33	2576.5	719.21	2049.5	2768.7	2.0419	6.6663	170
180	10.02	1.1274	0.1941	762.09	2583.7	763.22	2015.0	2778.2	2.1396	6.5857	180
190	12.54	1.1414	0.1565	806.19	2590.0	807.62	1978.8	2786.4	2.2359	6.5079	190
200	15.54	1.1565	0.1274	850.65	2595.3	852.45	1940.7	2793.2	2.3309	6.4323	200
210	19.06	1.1726	0.1044	895.53	2599.5	897.76	1900.7	2798.5	2.4248	6.3585	210
220	23.18	1.1900	0.08619	940.87	2602.4	943.62	1858.5	2802.1	2.5178	6.2861	220
230	27.95	1.2088	0.07158	986.74	2603.9	990.12	1813.8	2804.0	2.6099	6.2146	230
240	33.44	1.2291	0.05976	1033.2	2604.0	1037.3	1766.5	2803.8	2.7015	6.1437	240
250	39.73	1.2512	0.05013	1080.4	2602.4	1085.4	1716.2	2801.5	2.7927	6.0730	250
260	46.88	1.2755	0.04221	1128.4	2599.0	1134.4	1662.5	2796.6	2.8838	6.0019	260
270	54.99	1.3023	0.03564	1177.4	2593.7	1184.5	1605.2	2789.7	2.9751	5.9301	270
280	64.12	1.3321	0.03017	1227.5	2586.1	1236.0	1543.6	2779.6	3.0668	5.8571	280
290	74.36	1.3656	0.02557	1278.9	2576.0	1289.1	1477.1	2766.2	3.1594	5.7821	290
300	85.81	1.4036	0.02167	1332.0	2563.0	1344.0	1404.9	2749.0	3.2534	5.7045	300
320	112.7	1.4988	0.01549	1444.6	2525.5	1461.5	1238.6	2700.1	3.4480	5.5362	320
340	145.9	1.6379	0.01080	1570.3	2464.6	1594.2	1027.9	2622.0	3.6594	5.3357	340
360	186.5	1.8925	0.006945	1725.2	2351.5	1760.5	720.5	2481.0	3.9147	5.0526	360
374.14	220.9	3.155	0.003155	2029.6	2029.6	2099.3	0	2099.3	4.4298	4.4298	374.14

Source: Tables A-2 through A-5 are extracted from J. H. Keenan, F. G. Keyes, P. G. Hill, and J. G. Moore, *Steam Tables*, Wiley, New York, 1969.