A Study on Reliability Assessment Criteria of Diaphragm-type Accumulator for Intake and Exhaust Valve of Large Ship

Tae-Seok Kim[1], Jong-Jik Lee[2], Yong-Bum Lee[3], Byung-Oh Choi[4] and Han-Ju Yoo[5]

[1,2,3,4,5] Reliability Assessment Center, Korea Institute of Machinery & Materials, Daejeon, Korea

tskim@kimm.re.kr, ljjik@kimm.re.kr, lyb662@kimm.re.kr, bochoi@kimm.re.kr, aweek83@kimm.re.kr

ABSTRACT

A diaphragm type accumulator ("accumulator") is used in a wide range of hydraulic systems, especially the intake valve for fuel injection and the exhaust valve activated after a stroke in the electronic control unit of a ship to reduce shock waves and pulsation pressure and compensate for pressure.

In this application, the diaphragm operates in the same manner as in the engine operation mode (240 rev/min : 4 Hz) and is exposed to harsh conditions including abrupt surge pressure (ΔP).

Given these such conditions, the diaphragm is physically and structurally vulnerable to recurring faults.

While existing local and international assessment standards largely attribute faults in accumulators to damaged diaphragms, screws in the caps and body assemblies break due to structural problems. This leads to loss of functionality and safety issues instead of decreasing performance.

This study assumes that the main cause of faults in diaphragm type accumulators are damaged screws and explores the method of assessing reliability using pressure rating testing on a pressurized vessel of NFPA T/2.6.1 dimension. It also looks into a monitoring system to identify any N_2 gas leakage during testing.

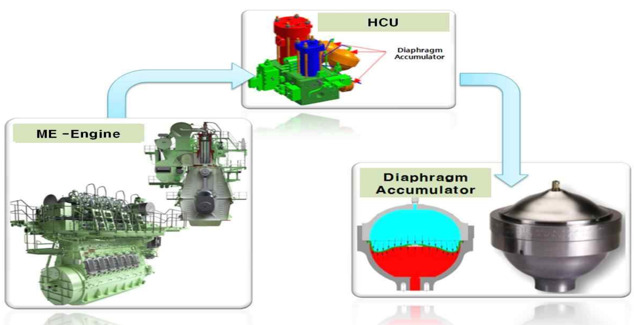


Figure 1 An accumulator for the intake and exhaust valves in a ship

1. COMPONENTS OF AN ACCUMULATOR AND CAUSES OF FAULTS

As shown in Figure 2, an accumulator consists of a gas valve, a cap, body, backup rings, a diaphragm, a valve button and others. In a ship, the cap and the body are coupled with screws so that the accumulator's supplies (i.e. diaphragm, backup ring) are easily replaceable. Therefore, the breakage of the coupling between the cap and the body due to cracking is the most serious type of fault. Reflecting on the history faults confirms that such kind of fault is the most common.

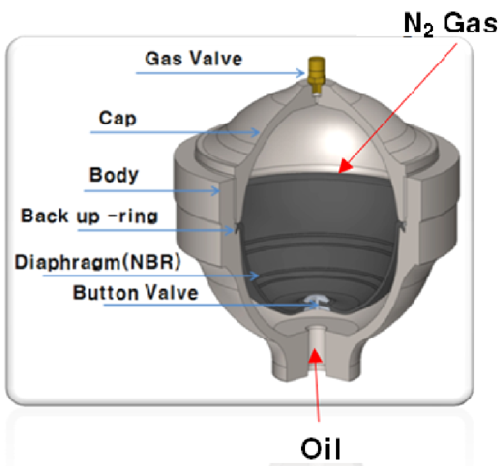


Figure 2 The components of accumulator

Figure 3 Main failure mode of accumulator

Figure 4 Other failure mode of accumulator

2. DESIGNING SERVICE LIFE TESTING

The warranted service life of an accumulator is assumed to guarantee life of 1.0×10^8 (life B_5) at a confidence level of 70 percent and with a reliability factor of 95%. Since the accumulator is similar to a pressurized vessel, the pressure rating test method for hydraulic vessels as prescribed in NFPA Specifications shall apply.

2.1. Introduction to "NFPA T/2.6.1"

The testing method proposed in the NFPA specifications is different from the existing one that applies Weibull distribution. As shown in Figure 5 and Table 1, strength distribution is applied. The largest difference is that acceptance is conditional upon zero failure after testing over the rated life (N) no matter how high the test conditions are elevated.

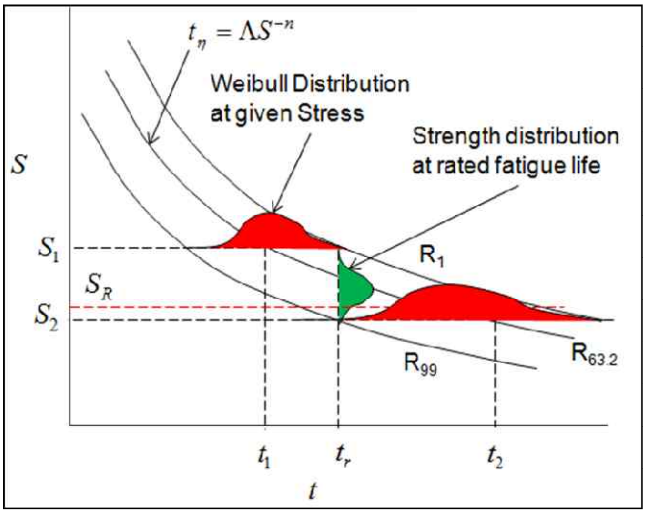


Figure 5 Comparison between Weibull distribution and Strength distribution

In the NFPA specifications, the cycle test pressure (CTP) is calculated by multiplying the rated fatigue pressure and the variability factor (K_V).

Table 1 Comparison between Weibull distribution and Strength distribution

Item	Life distribution	Strength distribution	Remarks
Application distribution	Weibull distribution	Normal distribution	
Distribution characteristic	Shape parameter(β)	coefficient of variation (κ_0)	
Warranty life	B_{100p}	Rated life, N	
Reliability	1-p	Assurance level $1-A_2$	Reliability = Assurance level
Confidence level	C.L	Verification level $1-A_1$	Confidence level = Verification level
Number of samples	n	N	
Acceptance criteria	No failure	No failure	
Test time	Non-failure test time(tn) or Accelerated life test time (ta)	Rated life, N	Regardless of the test conditions, Testing Rated life, N
Test conditions	Rated condition or Acceleration condition	CTP = RFP*Kv	- RFP : Rated fatigue pressure - CTP : Cyclic test pressure - Kv : Variability factor

2.2. Determination of coefficient of variation (k_0) and variability factor (K_V)

2.2.1 Determination of coefficient of variation (k_0)

Coefficient of variation (k_0) corresponds to the shape parameter (β) in Weibull distribution and shows the characteristics of strength distribution.

As shown in Table 2, the coefficient (k_0) depends on the material. The material of the accumulator's cap and body is SCM 440 which corresponds to Alloy, low. Therefore, the coefficient of variation is 0.14.

Table 2 Coefficient of variation by material

Metal		k_o
Steels:	Alloy, low	0.14
	Carbon, plain	0.08
	Nickel	0.10
	Stainless	0.09
	Tool	0.10
Iron		0.14
Nonferrous:	Aluminum (except 1100)	0.13
	1100 Series aluminum	0.23
	Cobalt	0.13
	Copper	0.09
	Magnesium	0.17
	Monel	0.27
	Titanium	0.12

2.2.2 Determination of variability factor (K_V)

The variability factor (K_V) is based on reliability (0.95), the confidence level (0.7), the number of samples (4) and coefficient of variation (0.14) and can be calculated as set out in Formula (1). Alternatively, a structured table as in Table 3 may be used. The variability factor is 1.18.

$$K_v = \frac{1+z_p k_0}{1-z_{A2}k_0}, \quad p = A_1^{\frac{1}{n}} \qquad (1)$$

Table 3 Variability factor (K_V)

Assurance Level	No. of Sample	K_0= Coefficient of variation of material														
1−A2	n	0.02	0.04	0.06	0.08	0.1	0.12	0.14	0.16	0.18	0.2	0.22	0.24	0.26	0.28	0.3
99.9%	1	1.08	1.16	1.27	1.36	1.52	1.69	1.89	2.14	2.47	2.89	3.48	4.36	5.78	8.51	15.87
99.9%	2	1.06	1.14	1.22	1.32	1.43	1.57	1.73	1.94	2.20	2.56	3.04	3.76	4.93	7.17	13.22
99.9%	3	1.06	1.12	1.20	1.28	1.38	1.51	1.65	1.84	2.08	2.39	2.82	3.46	4.51	6.51	11.91
99.9%	4	1.05	1.11	1.18	1.26	1.35	1.47	1.60	1.77	1.99	2.28	2.68	3.27	4.24	6.08	11.06
99.9%	5	1.05	1.10	1.17	1.24	1.33	1.44	1.57	1.73	1.93	2.20	2.58	3.13	4.04	5.77	10.45
99.9%	6	1.05	1.10	1.16	1.23	1.32	1.42	1.54	1.69	1.88	2.14	2.50	3.03	3.89	5.53	9.97
99.9%	7	1.04	1.10	1.15	1.22	1.30	1.40	1.52	1.66	1.85	2.09	2.43	2.94	3.76	5.34	9.59
99.9%	8	1.04	1.09	1.15	1.21	1.29	1.38	1.50	1.64	1.81	2.05	2.38	2.87	3.66	5.17	9.26
99.9%	9	1.04	1.09	1.14	1.21	1.28	1.37	1.48	1.61	1.79	2.02	2.33	2.80	3.57	5.03	8.98
99.9%	10	1.04	1.09	1.14	1.20	1.27	1.36	1.46	1.60	1.76	1.99	2.29	2.75	3.49	4.91	8.74
95.0%	1	1.04	1.09	1.14	1.20	1.26	1.32	1.39	1.47	1.55	1.65	1.75	1.86	1.99	2.13	2.28
95.0%	2	1.03	1.07	1.10	1.14	1.18	1.23	1.28	1.33	1.39	1.45	1.53	1.60	1.69	1.79	1.90
95.0%	3	1.02	1.05	1.08	1.11	1.14	1.18	1.22	1.26	1.31	1.36	1.42	1.48	1.55	1.63	1.71
95.0%	4	1.02	1.04	1.07	1.09	1.12	1.15	1.18	1.22	1.26	1.30	1.35	1.40	1.45	1.52	1.59
95.0%	5	1.02	1.04	1.06	1.08	1.10	1.13	1.16	1.19	1.22	1.25	1.29	1.34	1.39	1.44	1.50
95.0%	6	1.02	1.03	1.05	1.07	1.09	1.11	1.13	1.16	1.19	1.22	1.25	1.29	1.33	1.38	1.44
95.0%	7	1.01	1.03	1.04	1.06	1.08	1.10	1.12	1.14	1.16	1.19	1.22	1.25	1.29	1.33	1.38
95.0%	8	1.01	1.02	1.04	1.05	1.07	1.08	1.10	1.12	1.14	1.17	1.19	1.22	1.26	1.29	1.33
95.0%	9	1.01	1.02	1.03	1.05	1.06	1.07	1.09	1.11	1.13	1.15	1.17	1.20	1.23	1.26	1.29
95.0%	10	1.01	1.02	1.03	1.04	1.05	1.07	1.08	1.09	1.11	1.13	1.15	1.17	1.20	1.23	1.26
90.0%	1	1.04	1.08	1.12	1.16	1.21	1.26	1.31	1.36	1.42	1.49	1.55	1.63	1.70	1.79	1.88
90.0%	2	1.02	1.05	1.08	1.10	1.13	1.16	1.20	1.23	1.27	1.31	1.36	1.40	1.45	1.51	1.57
90.0%	3	1.02	1.04	1.05	1.08	1.10	1.12	1.14	1.17	1.20	1.23	1.26	1.29	1.33	1.37	1.41
90.0%	4	1.01	1.03	1.04	1.06	1.07	1.09	1.11	1.13	1.15	1.17	1.20	1.22	1.25	1.28	1.31
90.0%	5	1.01	1.02	1.03	1.04	1.06	1.07	1.08	1.10	1.11	1.13	1.15	1.17	1.19	1.21	1.24
90.0%	6	1.01	1.02	1.02	1.03	1.04	1.05	1.06	1.08	1.09	1.10	1.11	1.13	1.15	1.16	1.18
90.0%	7	1.01	1.01	1.02	1.02	1.03	1.04	1.05	1.06	1.07	1.08	1.09	1.10	1.11	1.12	1.14
90.0%	8	1.00	1.01	1.01	1.02	1.02	1.03	1.03	1.04	1.05	1.05	1.06	1.07	1.08	1.09	1.10
90.0%	9	1.00	1.01	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.04	1.04	1.05	1.05	1.06	1.06
90.0%	10	1.00	1.00	1.00	1.01	1.01	1.01	1.01	1.01	1.02	1.02	1.02	1.03	1.03	1.03	1.04

2.2.3 Calculation of cycle test pressure (CTP)

As mentioned earlier, the cycle test pressure can be calculated by multiplying the variability factor and the rated condition as below.

$$CTP = RFP \times K_v = 30.0MPa \times 1.18 = 35.5MPa \qquad (2)$$

Therefore, acceptance is granted when four accumulators are tested for 1.0×10^8 cycles under 35.5 MPa and experience no failure. Considering the lengthy testing period, accelerated life testing shall be conducted.

3. DESIGNING ACCELERATED LIFE TESTING

The primary cause of failure in an accumulator are damaged screws, and this can be accelerated by load. Therefore, pressure is used as an acceleration factor, and as shown in Figure 6, the fatigue and performance curve presented by ANSI/AGMA is used to calculate the acceleration index. The fatigue and performance curve is divided into two areas with different indices, and accelerated life testing conditions must be calculated using each index.

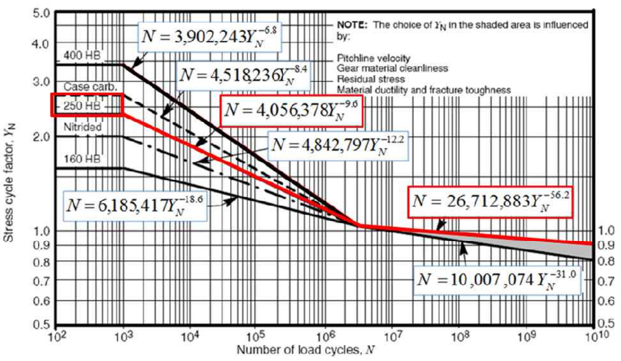


Figure 6 S-N curve

3.1 Calculating duration of accelerated life testing

From the curve in Figure 6, the index (n_2) for area 2 having a relatively moderate slope (after the knee) is 56.2, while the index (n_1) for area 1 (before the knee) is 9.6. The knee occurs in the 3.0×10^6 cycle.

3.1.1. Calculating the duration of accelerated life testing in area 2

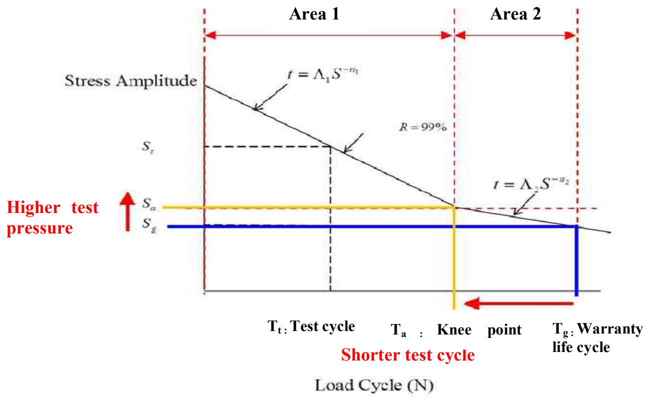


Figure 7 Acceleration in zone 2

In area 2, the testing up to 1.0×10^8 cycle (Tg) at 35.5 MPa (Sg) and the testing up to 3.0×10^6 cycle (Ta) at Sa are equivalent. Sa can be calculated as below.

$$S_a = S_g \times \left(\frac{t_g}{t_a}\right)^{\frac{1}{n_2}} = 35.5 \times \left(\frac{100{,}000{,}000}{3{,}000{,}000}\right)^{\frac{1}{56.2}} \qquad (3)$$
$$= 35.5 \times 1.064 = 37.7MPa$$

3.1.2. Calculating the duration of accelerated life testing in area 1

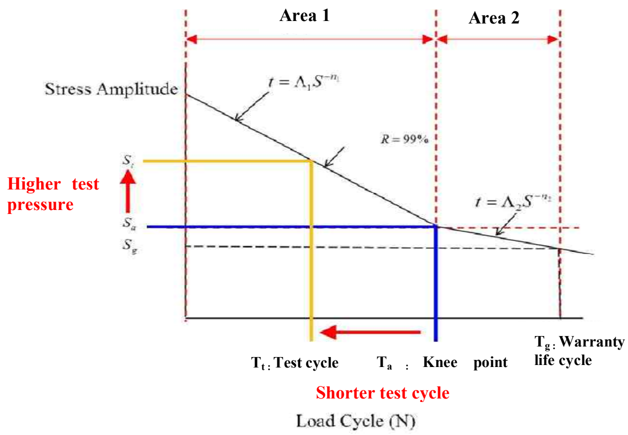


Figure 8 Acceleration in zone 1

In area 1, the testing up to 3.0×10^6 cycle (Tg) at 37.7 MPa (Sg) and the testing up to Tt cycle at St are equivalent. St is calculated such that it is close to 133 percent of the rated pressure that is the regular test condition for shock pressure.

The resulting value is 42.3 MPa, and Tt is calculated as below.

$$t_t = t_a \times \left(\frac{S_a}{S_t}\right)^{n_1} = 3{,}000{,}000 \times \left(\frac{37.7}{42.3}\right)^{9.6} \qquad (4)$$
$$= 988{,}221 \approx 1{,}000{,}000 \ cycle$$

4. Test method for accumulator's life

The test method for an accumulator's life consists of the following steps.

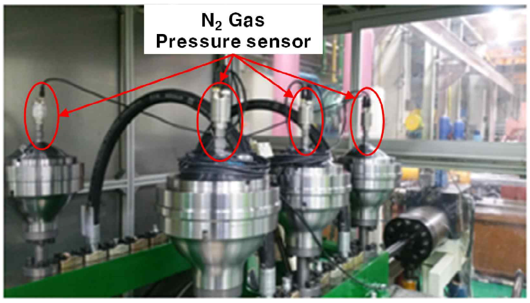
1) Install four accumulators in the test equipment that can create the same test conditions as those in Figure 9.

2) Apply pressure of 42.3 MPa for $1.0{\times}10^6$ cycles at a constant frequency of 1 Hz.

The B_5 life cycle of $1.0{\times}10^8$ is deemed to be guaranteed at a confidence level of 70 percent if none of the four accumulators suffers any failure during $1.0{\times}10^6$ cycles in life testing.

5. Monitoring system for any N_2 gas leakage

A system to monitor any leakage of N_2 gas during life testing was installed as set out below. A pressure sensor was installed on each accumulator gas valve, and peak values were derived from pressure waveform created during life testing to allow for monitoring of any pressure drop to identify any leakage.

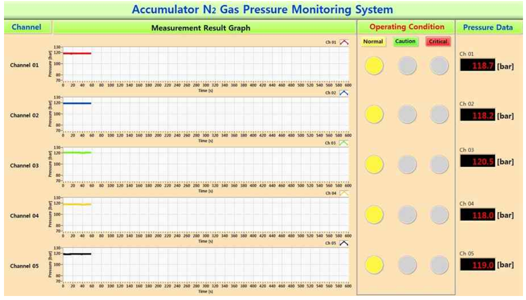


(a) N_2 Gas pressure sensor

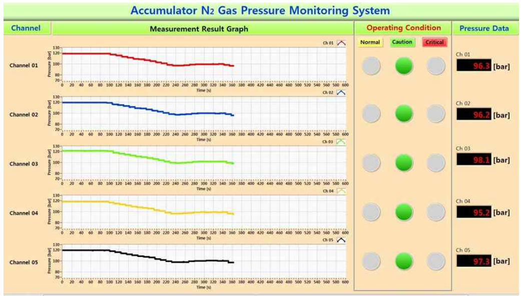
(b) DAQ & Program

Figure 9 N_2 Gas leakage monitoring system

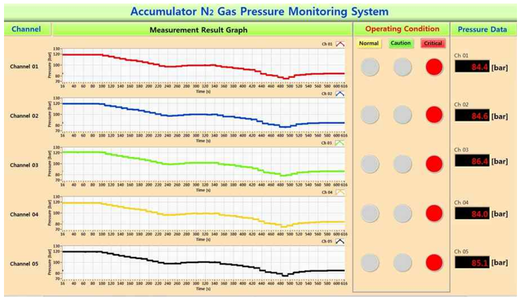
As shown in the monitoring concept in Figure 10, pressure drop is categorized into Normal, Caution and Critical.



(a) Operating condition level [Normal]



(b) Operating condition level [Caution]



(c) Operating condition level [Critical]

Figure 10 Monitoring system concept

6. CONCLUSIONS

The study assumed that the main causes of failure in accumulators are damage to screws in the coupling between the cap and the body and applied the pressure rating test method for hydraulic vessels as a valid life testing method in accordance with the NFPA specifications. Life testing for accumulators using strength distribution and accelerated life testing using pressure as an acceleration factor were suggested in the study. The study also proposes a system that can monitor any pressure drop to identify leakage in order to quantitatively determine any leakage of N_2 gas during life testing.

ACKNOWLEDGEMENT

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