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V. Kravchenko[1]**,** DSc, Prof.,
A. Vlasov[1]**,**
A. Andryushchenko[1]**,**
D. Vlasov[2]**,**
A. Golovchenko[1]**,**
P. Gavrilov[1]
[1] Odessa Polytechnic National University, 1 Shevchenko Ave., Odessa, Ukraine, 65044; e-mail: kravchenko@op.edu.ua
[2] State Professional School "Odessa Professional College of Marine Transport", 45 Primorskaya Str., Odessa, Ukraine, 65000

REDUCED AIR INJECTION TIME DURING CONTAINMENT TESTING DUE TO THE USE OF AN EJECTOR

В.П. Кравченко, А.П. Власов, А.М. Андрющенко, Д.В. Власов, А.М. Головченко, П.Г. Гаврилов. **Зменшення часу нагнітання повітря при випробуваннях герметичності захисної оболонки АЕС через використання ежектору.** При випробуваннях герметичності захисної оболонки (ЗО) і елементів системи локалізації аварії на АЕС України використовується метод «абсолютного тиску». За цим методом в результаті виміру тиску, температури та вологості повітря за рівнянням Менделєєва-Клапейрона визначається маса наявного в ЗО повітря. Тобто виток визначається непрямим шляхом через визначення зміни маси повітря в ЗО з часом. Випробування складаються з п'яти етапів: вакуумування; нагнітання повітря, для досягнення необхідного значення тиску; стабілізація параметрів; вимірювання; скидання тиску, і тривають більше 25 годин. Впродовж випробувань ніякі роботи в ЗО не проводяться. Необхідною умовою для випробувань є забезпечення надлишкового тиску у ЗО. Це здійснюється роботою компресора. Враховуючи великий об'єм ЗО, для цього потрібний відносно великий час, який впливає на економічні показники АЕС. В роботі запропоновано для зниження часу нагнітання повітря використовувати ежектор, робочою середою для якого є повітря після компресору. Середа для інжекції береться з навколишнього середовища (з «чистого» об'єму). В статті наведено розрахунок часу нагнітання компресором повітря до ЗО при сьогоднішніх умовах та при використанні ежектору. Тиск в ЗО при нагнітанні змінюється від 0 до 0,0686 МПа. Проведено оптимізацію тиску на виході ежектора для проектування відносно мінімального часу нагнітання. Оптимальний тиск на виході ежектора при проектування дорівнює 0,45 бар. Показано, що через використання ежектору час нагнітання може бути скорочений приблизно на 30 %.
Ключові слова: захисна оболонка, випробування на герметичність, компресор, ежектор

V. Kravchenko, A. Vlasov, A. Andryushchenko, D. Vlasov, A. Golovchenko, P. Gavrilov. **Reduced air injection time during containment testing due to the use of an ejector.** When testing the tightness of the containment and elements of the accident localization system at the Ukrainian NPP, the "absolute pressure" method is used. Using this method, as a result of measuring air pressure, temperature, and humidity, the Mendeleev-Clapeyron equation determines the mass of air present in the containment. That is, the turn is determined indirectly by determining the change in the mass of air in the containment over time. The tests consist of five stages: vacuuming; air injection, to achieve the required pressure value; parameter stabilization; measurement; pressure relief, and last more than 25 hours. During the tests, no work is carried out in the containment. A necessary condition for testing is to ensure overpressure in the containment. This is done by the operation of the compressor. Given the large volume of containment, this requires a relatively long time, which affects the economic performance of nuclear power plants. In this paper, it is proposed to use an ejector to reduce the time of air injection, the working environment for which is the air after the compressor. The environment for injection is taken from the environment (from the "pure" volume). The article calculates the time of air injection by the compressor to the containment under today's conditions and when using an ejector. The pressure in the containment changes from 0 to 0.0686 MPa during injection. The ejector outlet pressure is optimized for designing relative to the minimum discharge time. The optimal pressure at the ejector outlet during design is 0.45 bar. It is shown that due to the use of an ejector, the injection time can be reduced by about 30 %.
Keywords: containment, leak test, compressor, ejector

1. Introduction

The main equipment of the reactor unit, which is operated in Ukraine at NPP power units (mostly WWER-1000 reactors) is placed in cylindrical structures (containments) of prestressed reinforced concrete with a convex oval roof [1, 2]. Containments are designed for internal pressures up to 5 bar. Because concrete is not a dense barrier to gaseous media, the inside of the containment is lined with a dense metal coating of 8 mm thick. Thus, metal cladding provides the tightness of the containment and elements of the accident localization system and the forces that may occur under emergency conditions under internal pressure on the metal cladding are perceived by reinforced concrete containment.

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The strength of the containment is provided by pre-stressed steel cables, which pass in special channels in the wall and dome of containment [3]. Containment is also a barrier for radiation. The reliability of the system is checked by testing the tightness of the containment with excess internal air pressure and determine the integrated leakage from it, which is regulated [4].

Tests to determine the integrated leakage are carried out in several stages, namely [5]:

1. Vacuuming the containment to determine the location of leaks and eliminate damage – 4 hours.
2. Injection of air into the contaminant to the control pressure. Determination of leaks of nodes (main and auxiliary locks, hatch of transport corridor, etc.) 4.5 hours (for Rivne NPP).
3. Stabilization of parameters to align the parameters throughout the volume – 8 hours.
4. Measurements of temperature, pressure and humidity – 8 hours.
5. Pressure release – 1.5 hours.

The specified time of stages may be different for different NPPs and different power units for different reasons.

Thus, according to the method of “absolute pressure” to determine the integrated leakage, the value of which confirms the possibility of operation of the unit at power, it is necessary to spend more than a day. It should be added that no works in the containment during this period are not carried out. That is, the tests to determine the integrated leakage are on the critical path of the schedule of planned preventive work and should be reduced over time.

2. Analysis of literature data and statement of the problem

One of the stages of the test is the injection of air into the containment to a pressure of 0.0686+0.0196=0.0882 MPa (excess) [5]. To do this, a compressor carries out the air supply.

To reduce the time of air injection, it was proposed to use an ejector, which increases the flow of air at the outlet due to the suction of ambient air.

The aim of the work is to analyze the use of the ejector to accelerate the process of air injection during tests for the leak of the containment of NPPs with WWER. The calculations were performed on the example of Unit №3 of Rivne NPP.

From the experience of tests on the leak of the reactor unit with WWER-1000, located at the third and fourth power units of RNPP, it was found that:

– the free volume of the containment is 60,000 m^3;

– the compressor of the ЦК-135/8 brand is used to provide tests;

– at the beginning of operation of the compressor at pressure in containment of 0.101 MPa (abs.) pressure on a compressor pressure is equal to 0.245 MPa (excess).

According to [5], the rate of increase of pressure in containment should not exceed 0.039 MPa / hours). The tests shall be performed at a pressure of 0.0686 MPa. It follows that the minimum time of air injection can be equal to 0.0686 / 0.039=1.76 hours. This is 2.5 times less than the current injection time at RNPPs and significantly less than this value for other NPPs.

Given that the pressure behind the compressor at the beginning of the injection is 0.245 MPa (excess), ie at a pressure in the containment is 0.101 MPa (abs.), we can assume that the resistance of the path from the compressor to the containment is 0.245 MPa.

Nominal parameters of the compressor specified in the passport: $Q = 135$ m^3/min. at a pressure of P =0.667 MPa. The characteristics of the compressor are in the range of 0.42...0.6 MPa and $Q = 110...150$ m^3/min. [6]. Thus, during the period when the compressor increases the pressure in the containment from 0.101 MPa to 0.1696 MPa, the compressor operates out of operation.

Assuming that the resistance of the path from the compressor to the containment does not change when the pressure changes in the containment, we calculate the injection time according to the following algorithm.

The absolute pressure behind the compressor gradually increases from $P_1 = P_{\text{Containment}} + \Delta P_{\text{Resistance}} = 0.101 + 0.245 = 0.346$ MPa to $0.1696 + 0.245 = 0.4146$ MPa.

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According to the accepted pressure on the compressor P_1 determine the flow rate q (m^3/min). We accept the time interval τ (for example 10 minutes), during which the air flow will not change. Then, during this time to the containment will be submitted:

$$Q = q \cdot \tau,\ \text{m}^3. \tag{1}$$

Find the mass of air in the containment:

$$m = m_0 + \Delta m, \tag{2}$$

where m_0 – initial amount of air in containment;

Δm – mass of injected air:

$$\Delta m = Q \cdot \rho = Q \cdot 1.2041\ \text{kg}, \tag{3}$$

ρ – air density at 20 °C.

According to the Mendeleev-Clapeyron equation for an ideal gas we determine the corresponding pressure P_2, which will take place in the containment at a new mass of air:

$$P_2 = m \cdot R_\mu \cdot T / V. \tag{4}$$

If $P_2 < 0.1696$ MPa, repeat the calculation from the beginning, taking into account the new initial mass of air and the risk in containment.

Calculate the initial amount of air in the containment at atmospheric pressure. We assume air temperature = 293 K. The molar mass of air (oxygen – 21%, nitrogen – 78%, argon – 1%) is 29 kg/mol. Pressure in containment = 101 MPa.

Universal gas constant for air:

$$R_\mu = \frac{8314}{29} = 286.69 \frac{\text{J}}{\text{kg} \cdot \text{K}}. \tag{5}$$

Initial air mass:

$$m_0 = \frac{P \cdot V}{R_\mu \cdot T} = \frac{101325 \cdot 60000}{286.69 \cdot 293} = 72374.8\ \text{kg}. \tag{6}$$

From the analysis of the characteristics of the compressor ЦК-135/8 it can be noted that from 0.42 to 0.6 MPa, this characteristic is almost a linear function. As a result of the approximation we obtain the equation of the dependence of the specific air flow on the pressure after the compressor at $P = 0.10132 + 0.245 = 0.3463$ MPa:

$$q(P) = -21.775 \cdot P + 161.45\ \text{m}^3/\text{min}, \tag{7}$$

where P – compressor pressure, MPa;

$$q(P_1 = 0.3463\ \text{MPa}) = -21.775 \cdot 0.3463 + 161.45 = 153.91\ \text{m}^3/\text{min}.$$

It will be downloaded in 10 minutes:

$$Q = 153.91 \cdot 10 = 1539.1\ \text{m}^3.$$

Mass of this air:

$$\Delta m = Q \cdot \rho = 1539.1 \cdot 1.2041 = 1853.22\ \text{kg}.$$

Mass of air in containment in 10 minutes:

$$m = m_0 + \Delta m = 72374.8 + 1853.22 = 74228\ \text{kg}.$$

Pressure in containment in 10 minutes:

$$P = \frac{m \cdot R_\mu \cdot T}{V} = \frac{74228 \cdot 286.69 \cdot 293}{60000} = 103919\ \text{Pa}.$$

The results of further pressure changes in the containment with a time interval of 10 minutes are shown in Table 1.

Table 1

Calculation of the time to reach the pressure in the containment of 0.168 MPa

Time after start-up, min*	10	20	30	40	50	60	70
*P*co, MPa	0.10132	0.1039194	0.1065126	0.109105	0.1116963	0.1142868	0.116876
P_1, MPa	0.34632	0.3489194	0.3515126	0.354105	0.3566963	0.3592868	0.3618762
q, m^3/min	153.9054	153.8488	153.7923	153.7358	153.6794	153.6229	153.5665
dm, kg	1853.021	1852.339	1851.659	1850.979	1850.3	1849.62	1848.941
m_0, kg	72374.94	74227.96	76080.3	77931.96	79782.94	81633.24	83482.86
m, kg	74227.96	76080.3	77931.96	79782.94	81633.24	83482.86	85331.8
*P*co′, Pa	103919.4	106512.6	109105	111696.3	114286.8	116876.2	119464.8
Time after start-up, min	80	90	100	110	120	130	140
*P*co, MPa	0.1194648	0.1220523	0.124639	0.1272246	0.1298094	0.1323931	0.1349759
P_1, MPa	0.3644648	0.3670523	0.369639	0.3722246	0.3748094	0.3773931	0.3799759
q, m^3/min	153.5101	153.4538	153.3974	153.3411	153.2848	153.2285	153.1722
dm, kg	1848.262	1847.583	1846.905	1846.227	1845.549	1844.871	1844.194
m_0, kg	85331.8	87180.06	89027.65	90874.55	92720.78	94566.33	96411.2
m, kg	87180.06	89027.65	90874.55	92720.78	94566.33	96411.2	98255.39
*P*co′, Pa	122052.3	124639	127224.6	129809.4	132393.1	134975.9	137557.8
Time after start-up, min	150	160	170	180	190	200	210
*P*co, MPa	0.1375578	0.1401388	0.1427187	0.1452978	0.1478759	0.150453	0.1530292
P_1, MPa	0.3825578	0.3851388	0.3877187	0.3902978	0.3928759	0.395453	0.3980292
q, m^3/min	153.116	153.0598	153.0035	152.9474	152.8912	152.8351	152.7789
dm, kg	1843.516	1842.839	1842.163	1841.486	1840.81	1840.134	1839.458
m_0, kg	98255.39	100098.9	101941.7	103783.9	105625.4	107466.2	109306.3
m, kg	100098.9	101941.7	103783.9	105625.4	107466.2	109306.3	111145.8
*P*co′, Pa	140138.8	142718.7	145297.8	147875.9	150453	153029.2	155604.4
Time after start-up, min	220	230	240	250	260	270	
*P*co, MPa	0.1556044	0.1581787	0.1607521	0.1633245	0.165896	0.1684665	
P_1, MPa	0.4006044	0.4031787	0.4057521	0.4083245	0.410896	0.4134665	
q, m^3/min	152.7228	152.6668	152.6107	152.5547	152.4986	152.4426	
dm, kg	1838.783	1838.108	1837.433	1836.758	1836.084	1835.409	
m_0, kg	111145.8	112984.6	114822.7	116660.1	118496.9	120333	
m, kg	112984.6	114822.7	116660.1	118496.9	120333	122168.4	
*P*co′, Pa	158178.7	160752.1	163324.5	165896	168466.5	171036.1	

* *P*co – pressure in containment, P_1 – pressure before the ejector, *q* – specific air flow behind the ejector, *dm* – mass of air that will be pumped in the appropriate time to containment, m_0 – initial mass of air in containment before the start of the time interval, *m* – the available mass of air in the containment at the end of the considered time interval, *P*co′ – the pressure in the containment at the end of this time interval

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From the calculations it is obtained that the pressure in the containment of 0.1688 MPa will be obtained in 270 min = 4.5 hours. This practically coincides with the injection time on the 3rd and 4th units of RNPP.

Let's check the obtained result. At a containment pressure of 0.1688 MPa there will be the following mass of air:

$$m_f = \frac{P \cdot V}{R_\mu \cdot T} = \frac{168800 \cdot 60000}{286.69 \cdot 293} = 120571 \text{ kg.}$$

Thus, to achieve this pressure, the containment must be downloaded:

$$\Delta m = m_f - m_0 = 120571 - 72374.9 = 48196 \text{ kg.}$$

Appropriate air volume:

$$V = \Delta m / \rho = 48196 / 1.204 = 40030 \text{ m}^3.$$

The average feed of the compressor from table. 1 is equal to $q = 153.14$ m^3/min.

Thus, for the implementation of the injection will be required:

$$\tau = V / q = 40030 / 153.14 = 261.4 \text{ min.} \quad (8)$$

That is, a value is obtained that coincides with the previous value of the injection time.

Calculation of injection time using an ejector

The calculation of the ejector [7] is performed at the specified pressure before and after the ejector. At once there is a question: at what pressure behind an ejector it is necessary to carry out calculation. In the process of injection, the pressure in the containment varies from 0.1013 to 0.1696 MPa. That is, in any case, the designed device will work in a wide range of parameters. Thus, to determine the operating time of the compressor with the ejector before reaching the pressure in the containment of 1.72 bar (abs.), you must select the initial parameters, calculate the ejector, and then determine the flow of the ejector already specified design as a function of ejector pressure. As it is not known at which parameters the ejector operating time will be minimal, it is necessary to perform appropriate calculations for several ejector variants, calculated for different initial ejector pressures.

Here are the calculations of the first selected option. Since the ejector pressure varies in the specified range, an average pressure of 0.135 MPa was chosen for the calculation. At a compressor, pressure of 0.7 MPa, the pressure in front of the ejector is 0.45 MPa. Consumption of working air on the compressor 8000 m^3/h.

For the calculated design, the calculation of the change in parameters when changing the pressure in the containment (after the ejector) was performed. The results of the calculation - the dependence of air flow after the ejector on the pressure behind it (pressure in containment) are shown in Table 2.

Table 2

Characteristics of the ejector designed at P_{exit} = 0.135 MPa, with variable operation

<table>
<tr><th>P_{exit}, MPa</th><th>Ejection ratio, u</th><th>Flow rate after ejector, m^3/h</th><th>Flow rate after ejector, m^3/min</th><th colspan="2">Average flow rate in the pressure range, m^3/min</th></tr>
<tr><td>0.1551</td><td>0</td><td>8000</td><td>133.3333</td><td rowspan="2">140</td><td></td></tr>
<tr><td>0.1535</td><td>0.1</td><td>8800</td><td>146.6667</td><td rowspan="2">153.3417</td></tr>
<tr><td>0.1519</td><td>0.2</td><td>9601</td><td>160.0167</td><td rowspan="2">166.6833</td></tr>
<tr><td>0.1501</td><td>0.3</td><td>10401</td><td>173.35</td><td rowspan="2">180.0167</td></tr>
<tr><td>0.1485</td><td>0.4</td><td>11201</td><td>186.6833</td><td rowspan="2">193.35</td></tr>
<tr><td>0.1465</td><td>0.5</td><td>12001</td><td>200.0167</td><td rowspan="2">206.6833</td></tr>
<tr><td>0.1445</td><td>0.6</td><td>12801</td><td>213.35</td><td rowspan="2">220.0167</td></tr>
<tr><td>0.1423</td><td>0.7</td><td>13601</td><td>226.6833</td><td rowspan="2">233.35</td></tr>
<tr><td>0.1401</td><td>0.8</td><td>14401</td><td>240.0167</td><td rowspan="2">246.6833</td></tr>
<tr><td>0.1367</td><td>0.9</td><td>15201</td><td>253.35</td><td rowspan="2">260.0167</td></tr>
<tr><td>0.133</td><td>1</td><td>16001</td><td>266.6833</td><td rowspan="2">268.4</td></tr>
<tr><td>0.1279</td><td>1.0257</td><td>16207</td><td>270.1167</td><td></td></tr>
</table>

In the Table 2 in the last column shows the average flow in the pressure range given in the first column. That is, for example, when operating the ejector in the pressure range in the containment from 0.1279 to 0.123 MPa, the consumption of the ejector is 268.4 m^3/min. Until the pressure in the containment of 0.1279 MPa is reached, the flow rate behind the ejector is constant and equal to 270.11 m^3/min. After reaching the pressure in the containment of 0.1551 MPa, the flow rate of the ejector is equal to the flow rate of the compressor – 133.3 m^3/min. That is, you can bypass the ejector, which will even increase air consumption. With the help of the given data, the calculation of pressure change in containment over time was carried out. The calculation of the operating time of the ejector to achieve the desired pressure in the containment is given in Table 3.

Table 3

Calculation of the time of injection of air into the containment to achieve the required pressure of 0.1696 MPa using an ejector

Time after start-up, min	10	58.5	69.7	78.2	86.4	92	97.9
*P*co, MPa	0.1013	0.1240906	0.1279607	0.1330278	0.1367533	0.1401629	0.1423655
P_1, MPa	0.3463	0.3690906	0.3729607	0.3780278	0.3817533	0.3851629	0.3873655
q, m^3/min	270.12	270.12	268.40	260.02	246.68	233.35	220.02
dm, kg	3252.205	2764.374	3619.32	2661.045	2435.422	1573.339	1562.934
m_0, kg	72374.94	88635.97	91400.34	95019.66	97680.71	100116.1	101689.5
m, kg	75627.15	91400.34	95019.66	97680.71	100116.1	101689.5	103252.4
*P*co′, Pa	105878.2	127960.7	133027.8	136753.3	140162.9	142365.5	144553.7
Time after start-up, min	103.6	109.7	115	121.4	127.6	134.5	209.2
*P*co, MPa	0.1445537	0.1465394	0.1485275	0.1501355	0.1519337	0.1535362	0.1551645
P_1, MPa	0.3895537	0.3915394	0.3935275	0.3951355	0.3969337	0.3985362	0.4001645
q, m^3/min	206.68	193.35	180.00	166.68	153.34	140.00	133.33
dm, kg	1418.404	1420.04	1148.616	1284.369	1144.652	1163.064	11991.54
m_0, kg	103252.4	104670.8	106090.8	107239.5	108523.8	109668.5	110831.5
m, kg	104670.8	106090.8	107239.5	108523.8	109668.5	110831.5	122823.1
*P*co′, Pa	146539.4	148527.5	150135.5	151933.7	153536.2	155164.5	171952.7

According to the calculation, it was obtained that the set pressure of 0.17 MPa when using an ejector, which was designed for a final pressure of 0.135 MPa, will be achieved in $209.7 / 60 = 3.49$ hours which is $4.50 - 3.49 = 1.01$ hours less than without an ejector. Time savings of 23.5%.

Appropriate calculations were performed for the ejector designed for an outlet pressure of 0.125; 0.145; 0.156 and 0.17 MPa. The dependence of the injection time for different design pressure on the ejector is shown in Fig. 1.

In a result of the calculations, it was found that the minimum time of air injection in the containment to reach a pressure of 0.169 MPa is 3.09 hours (186 minutes) and corresponds to the design ejector pressure of 0.145 MPa.

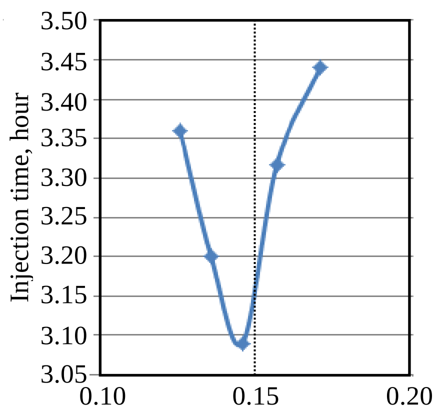

Fig. 1. Dependence of the time required for air injection in containment up to 0.1696 MPa, from the design pressure behind the ejector

Conclusion

1. When testing the tightness of the NPP containment, to reduce the time of air injection, it is proposed to use an ejector, which due to the working air from the standard compressor will suck air from the environment and thus increase air flow in the containment.

2. The calculation of the air injection time for today's conditions at the Rivne NPP was performed, the result of which coincided with the actual air injection time during the tests (4.5 hours). The characteristic of the compressor was used in the calculation, namely the dependence of the flow rate on the pressure in front of the compressor.

3. The program of calculation of an air ejector for work with the regular compressor of the ЦК-135/8Т brand for which initial data are initial and final air pressure, consumption of working air is developed.

4. The mathematical model of work of an ejector of the set design at work in a variable mode is developed. That is, the dependence of air flow on the ejector depending on the change in pressure behind it is determined.

5. With the help of the developed mathematical models, calculations were performed regarding the operating time of the ejector paired with the compressor to achieve a given ejector pressure of 0.17 MPa. As a result of calculations to determine the injection time depending on the design pressure on the ejector, it was determined that the minimum injection time is 3.09 hours, which is 1.48 hours (32.4%) less than under existing conditions. The optimal pressure behind the ejector for its design is a pressure of 0.145 MPa.

6. Reducing the time of containment tests will provide an opportunity to increase electricity generation and earn NPPs an additional profit of approximately $1.48\ h \cdot 10^6\ kW \cdot 0.6\ UAH/(kWh) = 888$ thousand UAH / year.

7. Under other conditions, it can be assumed that the reduction of injection time due to the use of the ejector will be about 30% of the available time.

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Кравченко Володимир Петрович; Volodymyr Kravchenko, ORCID: http://orcid.org/0000-0002-7557-3327
Власов Анатолій Петрович; Anatoliy Vlasov
Андрющенко Анатолій Михайлович; Anatoliy Andryushchenko, ORCID: http://orcid.org/0000-0003-1608-693X
Власов Дмитро Анатолійович; Dmitry Vlasov
Головченко Андрій Михайлович; Andrii Holovchenko, ORCID: https://orcid.org/0000-0002-7021-451X
Гаврилов Петро Георгійович; Petro Gavrilov

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