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The Research of PID Control in a Large Scale Helium Refrigerator

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Abstract. In the development of a helium refrigerator, the control of load temperature stability is an important requirement. We usually use multistage control strategies to achieve the precise control of it. Each level has its strict control logic. PID controllers are the core control module in the process. Therefore, a research of its principle and parameters' setting occupies an important position in the development work. This paper detailed describes the PID control principle used in a large scale helium refrigerator of 10kW@20K, as well as several improvements on PID parameters' setting, by using simulations and experiments in combination. The temperature is eventually controlled more precise.

1. Review

A 10kW@20K large scale helium refrigerator is developed by Technical Institute of Physics and Chemistry, Chinese Academy of Sciences. Its structure is shown in figure 1. It is mainly composed by compressor unit, heat exchanger, control valve, turbine expander, cold load, control load and so on. The refrigerator has only two active refrigeration sub-systems, one is the compressor unit, which supplies refrigeration power and refrigeration material, the other is the turbine expander, which expands the refrigeration material to supply the cold capacity [1].

From our system design goal, when the cold load changes, the controlled temperature should be adjusted stable in a range rapidly. The permissible range of temperature change is ±0.5K, and while the cold load reaches to 10kW, the stable temperature should not be over 20K.

To achieve the goal, temperature adjustments are divided into two levels: when temperature fluctuation is around ±0.35K, the control load is operated, with its maximum heating capacity 10% of system's refrigeration capacity; when temperature fluctuation is beyond ±0.35K, the temperature adjustment system would start adjusting the speed of the turbine expander. The first level adjusts temperature by the PID control loop of the control load, which would change the heating capacity of the control load to compensate temperature changes; and the second level adjusts temperature by the PID control loop of the control valve before the turbine expander, which would control the mass flow of refrigeration material, and then change the speed of the turbine expander as well as system's refrigeration capacity.

Keeping the high press and low press stable is the necessary condition of compressor unit's normal operation, which is usually archived by the PID control loops of valves in the gas management panel.

Compensation gas valve and exhaust valve are used for high press adjustment, while bypass valve is used for low press adjustment.

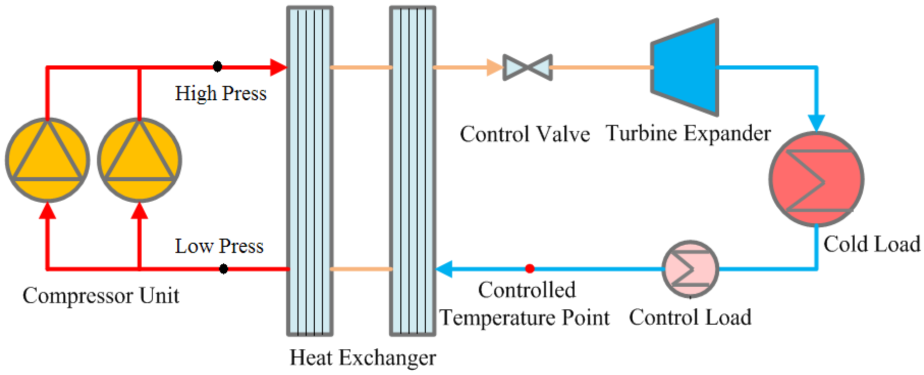

Figure 1. The principle diagram of 10kW@20K large scale helium refrigerator.

To archive precise PID controls, we should first establish a control system for the refrigerator. Seen from introduction of the system, there are many different kinds of signals, such as temperature, pressure, valve opening, flow, rotate speed, power, switching value and so on; those signals can easily reach to hundreds. And refrigeration equipments also have characteristics of large time-delay, strong non-linear, coupling of many factors and variable parameters. If using traditional relay circuit to control the system, there will be various components, which will make the control very complicated.

The 10kW@20K large scale helium refrigerator uses Siemens' S7-300 PLC to establish its automatic control system, and also implement PID algorithms. The Programmable Logic Controller (PLC) is based on a microprocessor. It is widely used in areas of industrial control. It uses a programmable memory to store and perform instructions, such as logical operation, sequential control, timing, counting, arithmetic operation and so on. And through digital and analog inputs and outputs, it can control various types of machinery and production processes [2]. This product uses program operations instead of complicated relay circuit operations, which makes it has more efficient at high performance, high reliability, flexible operation, easy to expand, friendly user interface and so on. The system's I/O Module cabinet is shown in figure 2.

Figure 2. The I/O Module cabinet of 10kW@20K large scale helium refrigerator.

2. The digital PID control principle in PLC S7-300

PID control law means putting the proportion (P), integral (I) and differential (D) of the deviation into a linear combination to make a control variable. Computer control uses a digital sampling PID controller, which calculates the control variable according to the deviation at sampling times [3].

The digital PID controllers of S7-300 PLC system are all integrated in its host-computer software called STEP 7. The controllers are provided to users in forms of encapsulated control blocks. Users can customize control parameters through block pins. S7-300 PLC has three kinds of digital PID controllers; they are SFB41/FB41 (CONT_C), SFB42/FB42 (CONT_S), and SFB43/FB43 (PULSEGEN). All the control loops of the 10kW@20K system have been using the FB41 (CONT_C) block. It uses a continuous control method; all the I/O variables of the block are continuous. The working principle of FB41 is shown in figure 3.

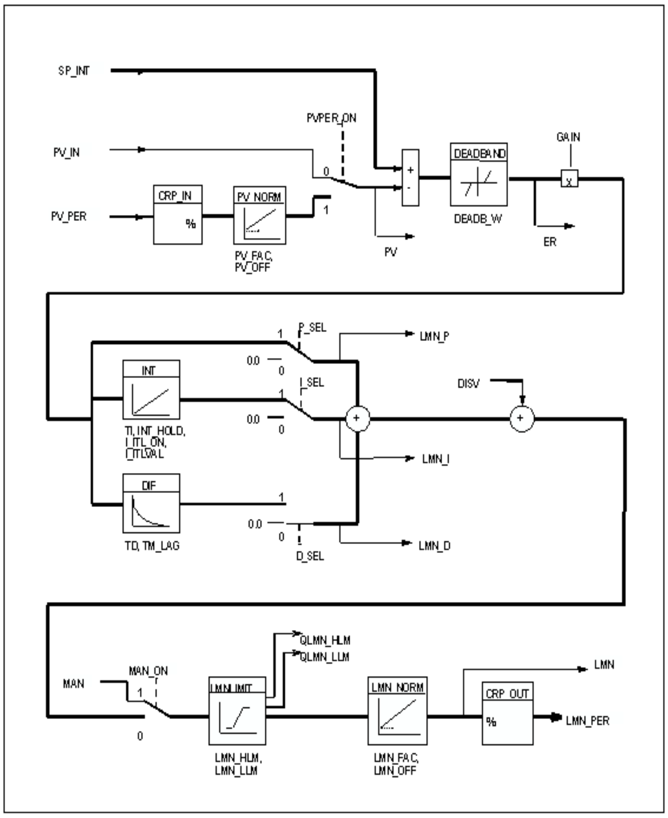

Figure 3. Working principle chart of FB41.

FB41 controller uses a position-type PID control algorithm. The calculation principle of its output control variable is as follows:

$$u(n) = K_{\mathrm{P}}\left\{ e(n) + \frac{T}{T_{\mathrm{I}}}\sum_{i=0}^{n} e(i) + \frac{T_{\mathrm{D}}}{T}[e(n) - e(n-1)] \right\} + M \tag{1}$$

In equation (1), e (n) is the deviation; M is the integral initial value; K_{P} is the proportional coefficient, its value is set through the GAIN pin of "CONT_C"; T_{I} is the integral time constant, set through the TI pin; T_{D} is the differential time constant, set through the TD pin; T is the sampling time, set through the CYCLE pin. The last four parameters are very important in digital PID control. Among them, CYCLE is the most difficult to be set.

Because the PID control for the system must strictly accurate, so we put FB41 into a cyclic interrupt block OB35 to execute. So the cyclic interrupt time of OB35 (100 ms default, can be set in the CPU Attribute Window) decides the calling time of PID algorithm. Every this time, OB35 performs the cyclic interrupt program once, and at the same time calls FB41 to adjust the process variable using PID algorithm. But the sampling time CYCLE of PID (1s default, can be set in the background data block of FB41) is used to control the input of FB41. Every this time, the input data of FB41 refreshes once. These two times are easy to be confused. When they are set different, it will cause FB41's integral output and differential output different from their theoretical calculation values. Then the PID parameters we obtained from theoretical analysis or historical experience will lose its reference value. When we enter the PID parameters into the control system, the system will be in a serious imbalance, and any fine-tuning is unable to make the system stable [4]. We have made some experimental studies on it.

For example, when using default calling time as 0.1s and default sampling time as 1s in STEP 7, we compare the experimental integral output of FB41 with its theoretical calculation value, setting K_P=5.3, T_I=180 and T_D =0. The result is shown in figure 4. We calculate the theoretical value by the Simulink software in MATLAB, setting its sampling time to 1s. When using both calling time and sampling time as 0.1s, the comparing result of the experimental integral output of FB41 and its theoretical calculation value is shown in figure 5, setting its simulation sampling time to 0.1s.

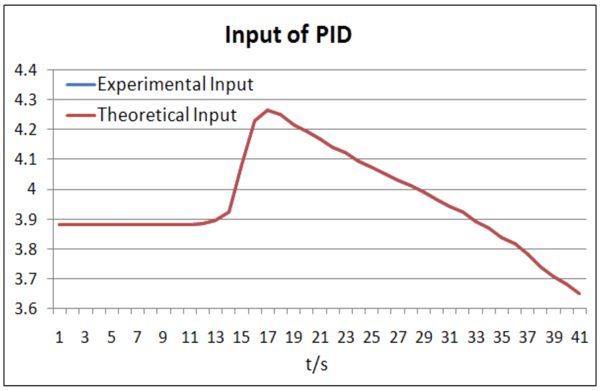

Figure 4 (a). Input of the PID controller with different calling time and sampling time in STEP 7.

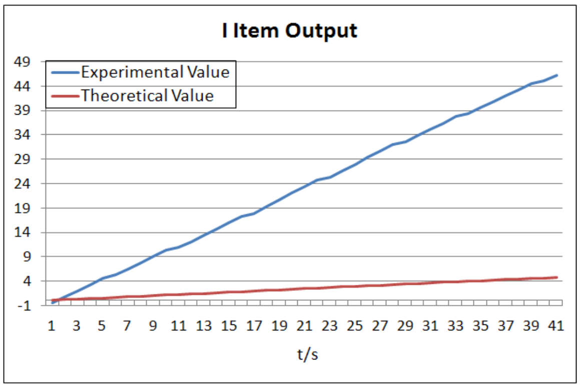

Figure 4 (b). Comparing result of the experimental integral output of FB41 and its theoretical calculation value, with different calling time and sampling time in STEP 7.

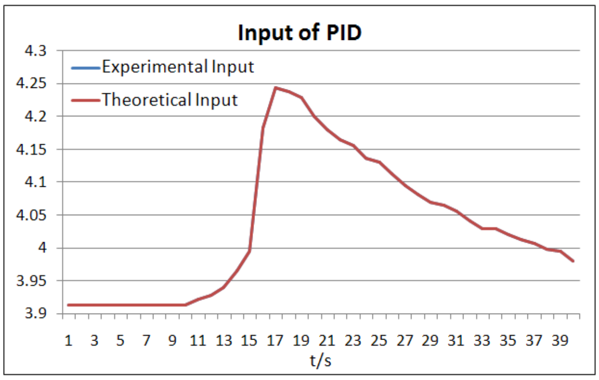

Figure 5 (a). Input of the PID controller with the same calling time and sampling time in STEP 7.

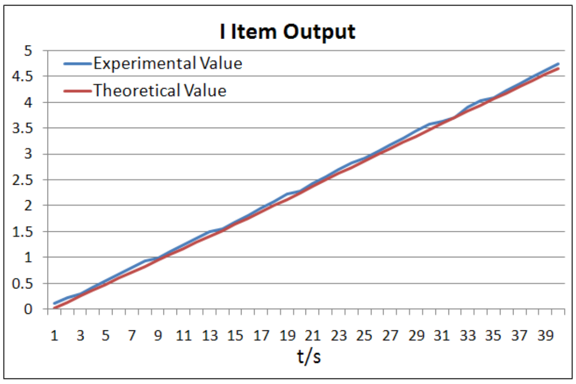

Figure 5 (b). Comparing result of the experimental integral output of FB41 and its theoretical calculation value, with the same calling time and sampling time in STEP 7.

From figure 4 and figure 5, we see that when the sampling time is not consistent with the calling time, the integral item output value will serious mismatch with its theoretical calculation value. Only when this two time is the same, can the output of the integral item to be consistent with its theoretical value. The result also applies to the differential item. So when using FB41, we should pay attention to set the calling time and sampling time same, so that the system can come to the stated goal of stable only by a fine-tuning. This way can save us a lot of debugging time.

3. PID control loops in the refrigerator

The structure principle of PID control loops in 10kW@20K system is shown in figure 6. Inside figure 6, the small box encloses the part performed by digital PID controllers, and the big box encloses the part performed by S7-300 PLC. When the controlled object deviates from its set point, the PID controller will calculate a movement using equation (1) to cause actuator acting for adjusting the controlled object close to its set point value.

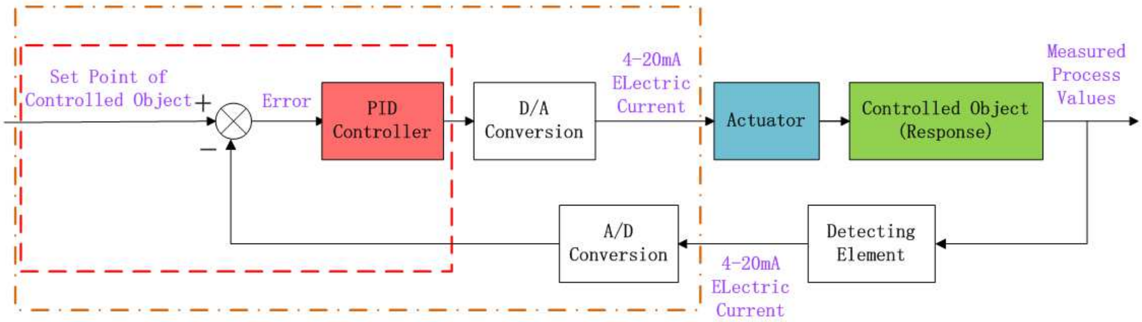

Figure 6. The structure principle of PID control loops in 10kW@20K refrigerator.

In 10kW@20K system, there are five PID control loops in total. Each loop's actuator and controlled object is described in table 1. For different actuators and controlled objects, the demand of its PID response is not the same; so their PID parameters must be different.

Table 1. PID control loops in 10kW@20K refrigerator.

Controlled Object	Actuator
High press	Compensation gas valve
	Exhaust valve
Low press	Bypass valve
Turbine expander speed	Control Valve
Temperature	Control load

4. Research on PID parameters' setting

The PID adjustment refers to set control parameters K_P, T_I and T_D reasonably. That makes the controlled object acts in the ideal way to its set point with the response speed as quick as possible, and the overshoot volume as small as possible. So we need to learn the influence of each parameter for the PID adjustment.

4.1. *The adjust effect of each control parameter*. Once a deviation appears, the proportional controller immediately makes the deviation decrease, and its adjusting effect is very fast. Larger the proportion coefficient is, stronger the proportional effect is. But to a system of self-balance, if it only uses a proportional controller, it will have a static error in final. Although increasing the proportion coefficient can reduce the error, but an excessive proportion coefficient can cause an oscillation of the controlled object, even lead to instability of the loop system.

In order to eliminate the static error, we need to add an integral controller on the basis of the proportional controller. So, as long as the deviation is not 0, the controlled object will be influenced by its cumulative effect to reduce it. Until the deviation comes to 0 and the control function no longer changes, can the system achieve stability and the static error be eliminated. While the integral action eliminates the static error, the response speed is reduced. Larger the integral time constant is, weaker the integral effect is. At the same time, the static error will be eliminated more slowly, and the overshoot volume will be smaller.

In order to speed up the control process, it is necessary to make instant response to not only a deviation but also its change once the deviation appears. This can eliminate the deviation in the process. And a differential controller just plays this role [5]. Larger the differential time constant is, stronger the differential effect is, and faster response to the change of deviation is. This is helpful to speed up the system's action. But an excessive differential coefficient can easily make the instant change volume too large, which will cause a signal burr, even system damage.

After mastering the function of each control parameter and the change requirement of controlled object, we have finished the PID adjustment. Here are some experimental instances of PID control adjustment.

4.2. *Experimental instances of PID adjustment.* For example, after system on, the requirement of the compensation gas valve is to keep the high pressure value not overshoots and its opening must be a small value when the high pressure reaches its set point. The response speed should be considered in the last. Firstly, we use the experience coefficients of K_P=5.3, T_I=180 and T_D=0, and get the adjusting effect as shown in figure 7. The upper curve is high pressure, and the lower curve is the opening of compensation gas valve.

Figure 7 shows the high pressure has an overshoot under these control parameters. And the valve opening is 85% when the high pressure reaches its set point value, and then the valve is closed directly to 0 opening. This causes a large impact to the valve, and is not what we expect of its action trend. The ideal trend should be that, when the high pressure comes near to its set point value, the valve opening begins to fall, and when it reaches the set point value, the valve opening should become relatively small. So we should strengthen the proportional effect and weaken the integral effect that means enlarging both K_P and T_I. We use K_P=10, T_I=3000 and T_D=0 in final, getting the ideal adjusting effect shown in figure 8.

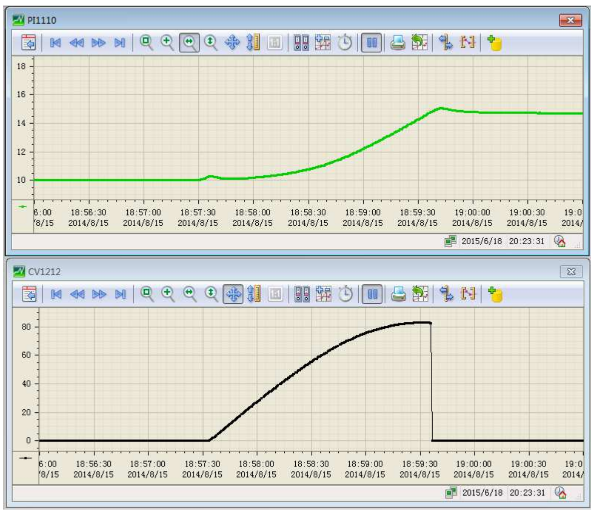

Figure 7. Adjusting effect of high pressure supply when K_P=5.3, T_I=180.

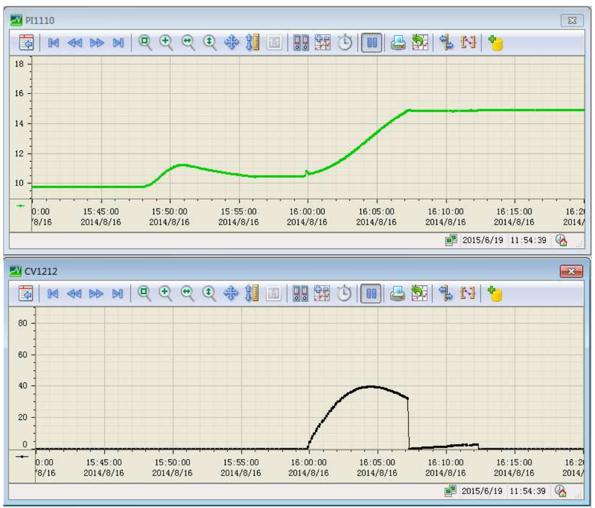

Figure 8. Adjusting effect of high pressure supply when K_P=10, T_I=3000.

From figure 8, we see that although the response time changes into 7 minutes from 2 minutes, but it's still in the range of permission. But the high pressure does not overshoot, and the valve is closed at the opening of 32.5%, which is significantly smaller than figure 7.

For another example, the requirement of the bypass valve is to quickly response when the low pressure deviates from its set point value. The low pressure can overshoot but better not too much. Firstly, we use the experience coefficients of K_P=55, T_I=180 and T_D=0, and find that the response is not fast enough, leading to large fluctuation of low pressure, as shown in figure 9. The upper curve is low pressure, and the lower curve is the opening of bypass valve.

At this time, we should decrease T_I to speed up the response, and decrease K_P to avoid too large overshoot at the same time. The final ideal adjusting effect is shown in figure 10.

Figure 9. Adjusting effect of low pressure when K_P=55, T_I=180.

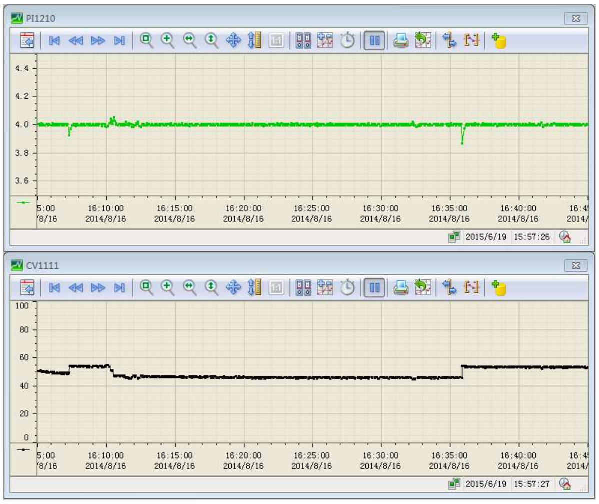

Figure 10. Adjusting effect of low pressure when K_P=50, T_I=100.

Figure 10 shows that the adjusting time of the low pressure is in second range. The response is quick enough, and the overshoot is small. This makes the low pressure fluctuation in a small range, and the effect is ideal.

We can set parameters of other PID control loops in the same way with its own adjusting demand. And parameter values of each PID control loop are listed in table 2.

Table 2. PID coefficients at present.

Controlled Loop	K_P	T_I	T_D
Compensation gas valve	10	3000	0
Exhaust valve	-82	190	0
Bypass valve	50	100	0
Turbine expander	0.2	100	0
Control load	300	1200	0

5. Stable running results of the refrigerator

With reasonable control parameters, the 10kW@20K large scale helium refrigerator has successfully run for 72 hours, and its controlled temperature hold steady at 19.7K±0.3K, while the load heating at 10.7kW±0.3kW. The result is shown in figure 11.

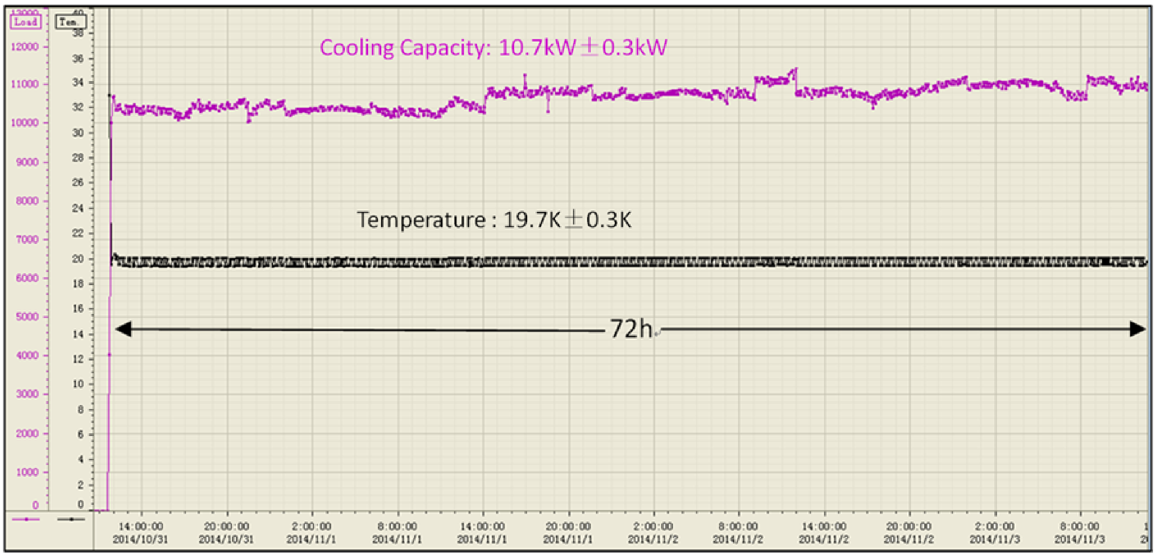

Figure 11. Stable running result of 10kW@20K large scale helium refrigerator.

From figure 11, we see that the temperature is controlled to the target value well. The PID control parameters are set suitably.

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