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LHC cryogenic system adaptation and recovery after a major insulation vacuum breakage in a final focusing superconducting magnet in 2023

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Abstract. On 17th of July 2023, during the LHC (Large Hadron Collider) beam operation for physics Run 3, one of the low-beta superconducting quadrupole located on the left side of the LHC point 8 (ITL8) quenched following an electrical network disturbance. This quench unfortunately induced a crack in one of the magnet interconnection bellows, provoking a large leak between the cold mass cryogenic helium vessel maintained at 1.9 K and its insulation vacuum. As result, the magnet rapidly warmed-up and a repair was mandatory to restart the LHC. To avoid a full LHC sector warm-up/cooldown over 3 km heavily impacting the physics schedule, it has been decided, after careful risk analysis to ensure personnel's safety at highest priority, to repair the magnet interconnection bellows in-situ, by locally warming up to room temperature, while letting the remaining of the LHC sector drifting in temperature, setting however an upper limit in temperature (80 K) limiting the available time for repair to 10 days. This scenario, originally not foreseen in the cryogenic operation procedures, was immediately studied and validated using cryogenic dynamic simulations in very short time and a repair plan of the identified faulty bellows was rapidly setup and achieved thanks to an impressive joint effort of many different CERN teams to minimize the LHC downtime. This paper describes this exceptional procedure of partial-local warm-up, the re-qualification of the helium circuits after the repair, and the re-cooldown of the machine to its nominal operating temperature thus allowing the LHC machine to resume operation for physics.

1 Introduction

The LHC (Large Hadron Collider) cryogenic system is divided in eight equivalent sectors of 3.3 km each, maintaining superconducting magnets at 1.9 K with superfluid helium. While the LHC was under nominal beam operation during the night of the 17th of July 2023, an electrical disturbance was induced on the electrical network because of a fallen tree on a high voltage line located at about 50 kilometers from CERN. This electrical disturbance caused a trip of the LHC Radio-Frequency cavities that dumped the beams and 370 milliseconds later, three quadrupole magnets quenched at full current due to a spurious Quench Protection System (QPS) trigger, a usual sequence for this kind of event that occurs few times a year.

All the three quenches induced expected magnet discharges without any anomalies found in the post-mortem data but unfortunately, one of this quench induced a significant breakage of the insulation vacuum in one of the final focusing low-beta quadrupole located at the left side of the LHC point 8 called *Inner Triplet Left of 8* (ITL8). The LHC Inner Triplet is an independent set of three interconnected superconducting quadrupoles operating at 1.9 K. They represent a cold mass of 22 tons over 30 meters [1] and are located at the extremity of the cryogenic sector to focalize the beams before the collisions. They are separated by about 200 meters from the rest of the

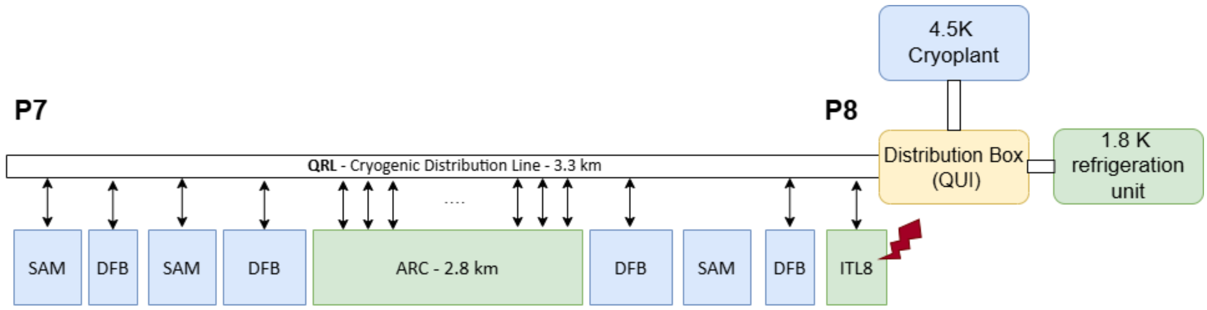

Figure 1. LHC cryogenic sector 7-8 with the Inner Triplet Left 8 (ITL8) at the right extremity

continuous ARC cryostat, and cooled by the same cryogenic distribution line (QRL) that is common to the ARC and the Inner Triplet but with the capability to isolate each circuit, see Figure 1.

Just after the quench, the Inner Triplet magnets rapidly warmed-up towards room temperature at about 1 *K* per minute, and the LHC could not restart until a solution is found as these magnets are mandatory to operate the machine. Figure 2 represents the insulation vacuum pressure of the Inner Triplet, the cold mass pressure, and the temperature of the ITL8 after the quench that occurred at time t=0. We clearly see that the vacuum pressure converges to the cold mass pressure after 6 hours. During this event, no helium was released to atmosphere but the Inner Triplet cold mass was pressurized to 18 bara as it is the case after a quench and the helium was then depressurized and recovered via the quench valves connected to the QRL that remained fully operational with the rest of the ARC as the insulation vacuum of the ITL8 and the QRL are independent.

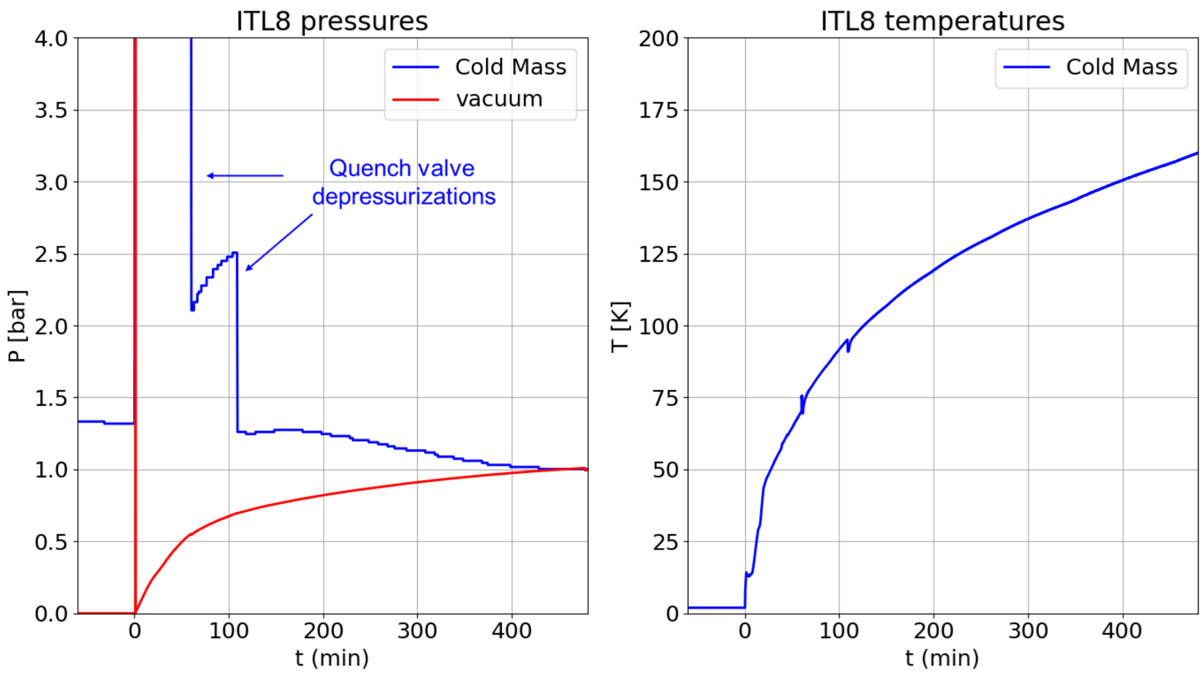

Figure 2. ITL8 pressures/temperature just after the quench and the insulation vacuum breakage

It is worth mentioning that despite this unlikely event, all protection systems worked as expected without impacting the personnel safety and the integrity of equipment, even if the sudden vacuum breakage released a large amount of energy and condensed the air around the magnet cryostat during its fast warm-up, see Figure 3.

2 First diagnostics

The very first test consisted in pressurizing the cold mass between 1 *bar* and 3 *bar* while pumping the insulation vacuum at 700 *mbar*. It was immediately noticed that the insulation vacuum pressure was directly influenced by

Figure 3. Inner Triplet L8 in the LHC tunnel during a visual inspection 12 hours after the event

the cold mass pressure, confirming a leak evaluated at about 2000 $mbar \cdot l/s$ from the pressure rise as function of the ΔP between the cold mass and the insulation vacuum. The first difficulty was then to identify the possible location of this leak, most probably in one of the three magnet interconnections containing 14 lines which of 3 lines (M1, M2 and M4) are equipped with edge-welded bellows that are the most fragile components, see Figure 4.

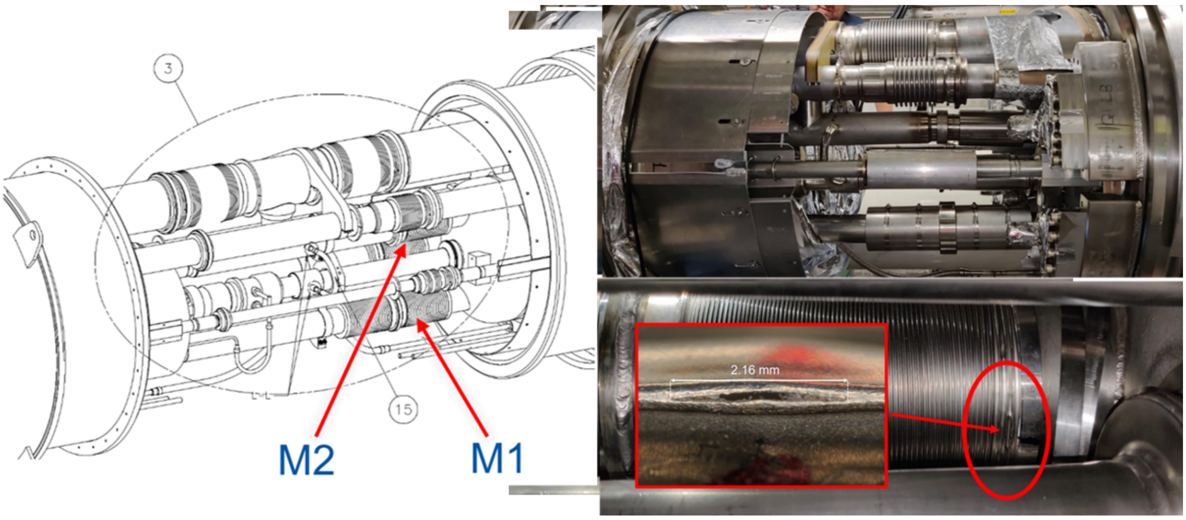

Figure 4. Inner Triplet interconnection and leak identification on the M2 bellows

After only few hours, a vibration measurement using accelerometers was successfully implemented in situ by the CERN Mechanical Measurement Lab on the three Inner Triplet interconnection envelopes. A set of measurements was recorded at high frequencies (up to 12 kHz) for different pressure differences between the cold-mass and the insulation vacuum to detect a potential vibration on the external envelope if helium is released towards the insulation vacuum. After signal analysis using a Fast Fourier Transform of the accelerometer measurements, it was clearly noticed that the interconnection *Q1-Q2* had a different signature when the pressure in the cold mass was higher, indicating a potential release of helium at this location, see Figure 5. This interconnection was consequently opened (the so-called *W bellows* on the external magnet envelope was removed) four days later after having setup the 3 km sector in cold standby at 20 K for safety reasons while the inner triplet was at the ambient temperature. Finally, a leak of few mm^2 was noticed and measured on the so-called *M2 bellows* allowing the passage of instrumentation cables between magnets, see Figure 4.

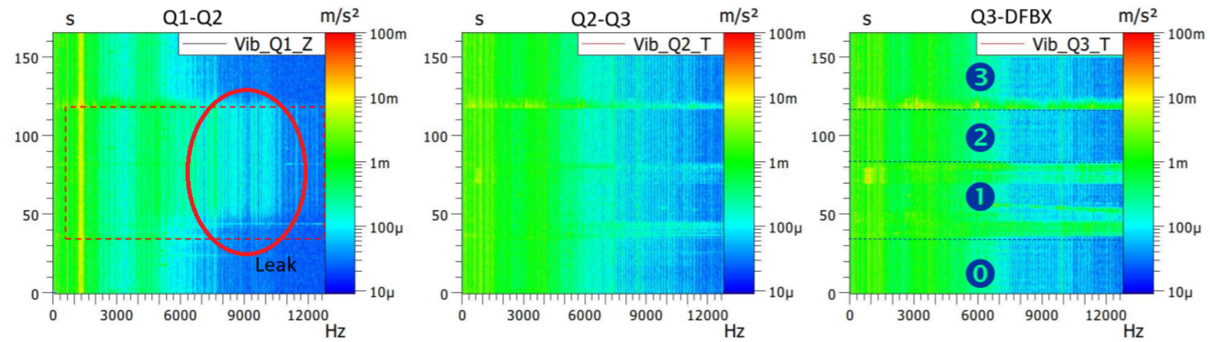

Figure 5. Vibration measurement results (in the frequency domain) over the three magnet interconnections used to localize the leak by the CERN Mechanical Measurement Lab

3 Reparation scenarios

To resume the LHC operation, it was mandatory to exchange this damaged M2 bellows in order to re-cooldown this inner triplet at cryogenic temperature and make it operational again for the beams. The baseline procedure for such an intervention requires a complete warm-up of the corresponding LHC sector over 3.3 km. This heavy procedure takes at least 3 months (warm-up, repair, cool-down, recommissioning) and would have entirely canceled the LHC physics program for the rest of 2023. A series of alternative scenarios were consequently studied to replace in-situ the damaged bellows with the rest of the ARC at cryogenic temperatures above 20 K. After a risk analysis summarized in Table 1, it was concluded that :

- all the helium circulation in the cryogenic circuits must be stopped;
- all the cryogenic circuits must be depressurized to atmospheric pressure;
- all the ARC cold masses must remain below 80 K to reduce the risk of damaging any other mobile devices in the machine such the RF fingers located inside the Plug-In-Module (PIM) installed in all the magnet interconnections and which can be dislodged during their warm-up above 80 K [2].

As consequence, all the cryogenic circuits and ARC cold masses will drift in temperature during the bellows replacement at about 2.5 K/day. It is also important to note that after the intervention, about 10 days are necessary before resuming the ARC cooldown where the following sequence must be ensured:

- Closure of the triplet interconnection and leak tests.
- Local reconditioning of the triplet cryogenic circuits and the cold mass volume using the pressure sensor internal piping.
- Operational pressure test of the triplet cold mass with the newly installed bellows.
- Unlock of the triplet cryogenic circuits and reconnection of the cryogenic distribution line at about 250 K to limit the temperature gradient over the magnets.
- Re-cooldown of the triplet to about 80 K before reconnecting the rest of the ARC at a similar temperature to resume the entire sector cooldown.

Dynamic simulations were consequently conducted with the EcosimPro simulation software using the CRYOLIB library to evaluate the ARC temperature drift. Figure 6 represents the simulations results obtained with an existing LHC cryogenic model developed previously to evaluate the helium inventory evolution after a major power failure [3] where the conduction and radiation losses were applied on the different cryogenic circuits and masses. It was demonstrated that to maintain the ARC cold mass temperatures below 80 K, the bellows need to be repaired in less than 10 days to have a total ARC cooling interruption of less than 20 days. The *scenario B* of the Table 1 was finally retained and agree by all the stakeholders.

Table 1. Possible reparation scenarios with their associated risks

	Opening what?	How Long ?	ARC temperature	Risks
A	W bellows	< 3 days	ARC < 30 K	Low
B	M bellows	< 10 days	ARC < 80 K	Medium
C	M bellows	> 10 days	ARC > 80 K	High
D	QRL lines	any	ARC > 100 K	Not acceptable

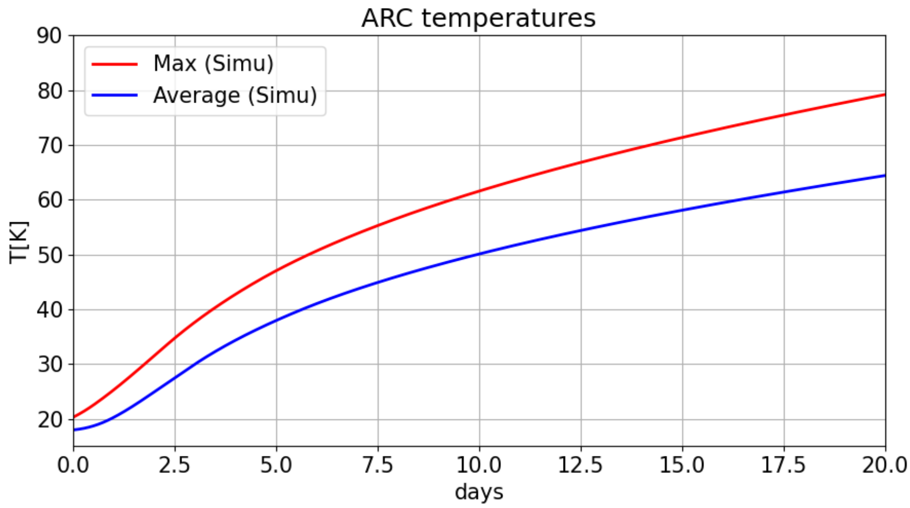

Figure 6. Simulation results of the ARC temperatures after a cooling interruption from 20 K. The *Average* (blue) corresponds to the middle of the ARC and the *Max* (red) to the ARC extremities close to the cold-warm transitions

4 Obtained results

Finally, the CERN magnet and mechanical groups managed to replace in-situ the M2 bellows in only 4 days and the ARC cooldown was resumed 9 days later, resulting to an ARC cooling interruption of 13 days as represented in Figure 7. Then, 8 days were needed to reach the cryogenic nominal temperature of 1.9 K in the entire sector and 12 days were needed to recommission the powering circuits before re-injecting the beams. Finally, the beam interruption was ”only” 45 days and the LHC ion run 2023 was ensured despite a reduction of the proton physics run.

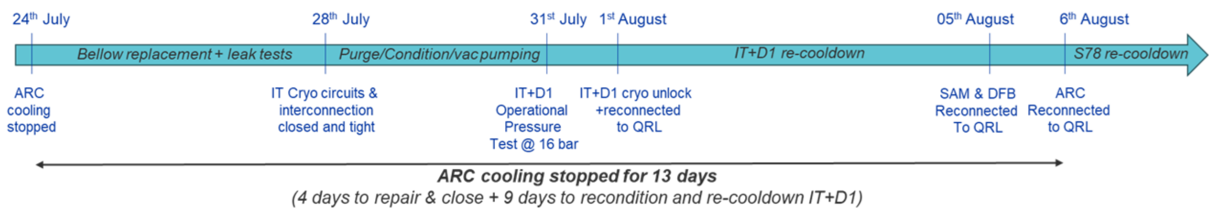

Figure 7. Timeline of events during the ARC active cooling interruption

The ARC temperature drift did not completely behave as expected with respect to the simulations for various reasons, see Figure 8. First, the ARC extremities simulation was considering an additional heat load of about 100 W due to the cold-warm transition at these locations but we observed a much higher heat load on the ARC right extremity, resulting in a faster warm-up on this side.

Then, due to some leaks into the insulation vacuum of this sector, some unexpected degassing process occurred at about 40 K : the pressure of the ARC insulation vacuum went suddenly from a value of 10^{-6} *mbar* to 10^{-3} *mbar* due to the active pumping system that was not strong enough to absorb this unexpected degassing. Consequently the warm-up of the magnets was accelerated as it is well visible on Figure 8. It took half a day to install some additional vacuum pumping groups to recover a correct insulation vacuum and a reasonable warm-up speed.

The dynamic model developed for these simulations can nevertheless be validated assuming that the insulation vacuum is not degraded and that there is no additional heat loads on the cold-warm transition at the ARC extremities because the ARC left extremity behaved as expected, as well as the ARC standard cells during the six first days while the insulation vacuum was correct. About the additional heat load on the ARC right extremity, it was estimated at about 140 W instead of the expected 100 W due to the surrounding Distributed Feed Box (DFB) that also warmed-up. As consequence, the allocated time for the repair should be 4 days to not overpass the 80 K in the ARC or 7 days to not overpass the 100 K.

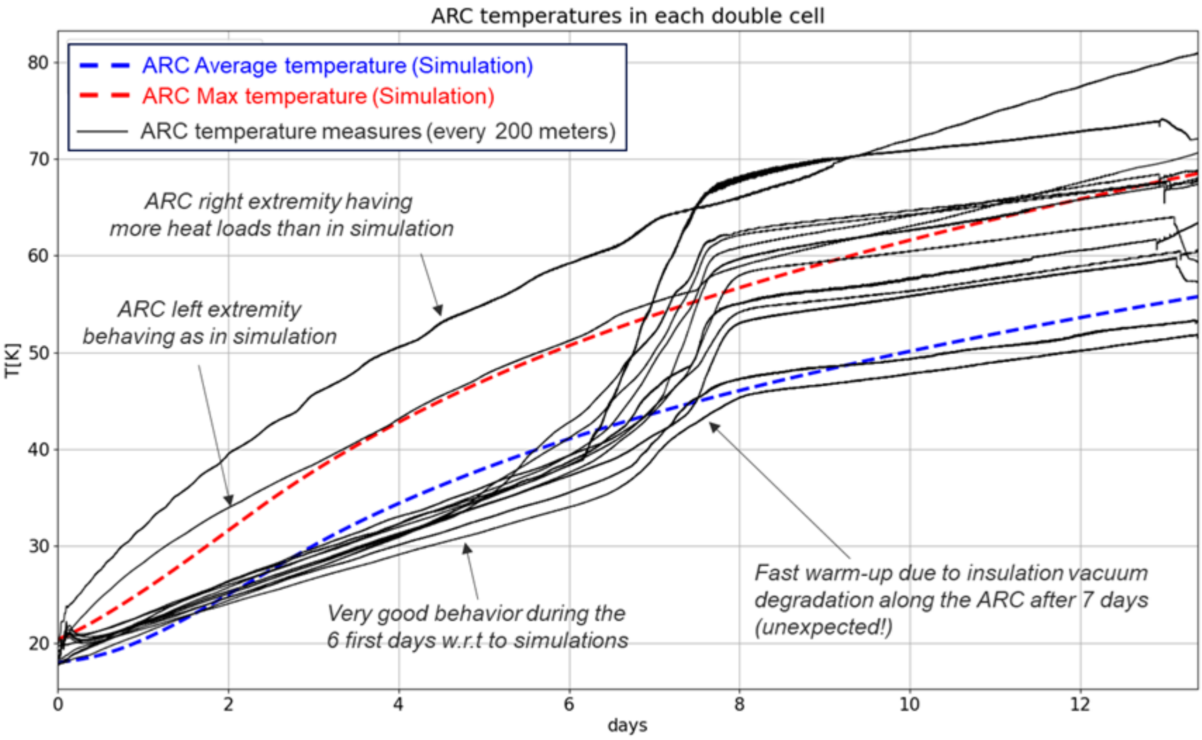

Figure 8. ARC temperature measurements during the active cooling interruption compared to the simulations

5 Conclusion

The LHC beam operation year 2023 was marked by an unprecedented unlikely event due to a edge-welded bellows failure following a quench in the the Inner Triplet L8 of LHC. Nevertheless, the damaged bellows was quickly identified thanks to a vibration analysis using accelerometers on the magnet interconnection envelope. An in-situ reparation of the damaged bellows was rapidly achieved while keeping the rest of the ARC at cryogenic temperatures between 20 K and 80 K to avoid any risk for the personnel and the degradation of sensitive equipment. Then, a non-conventional cryogenic recovery sequence was proposed and successfully implemented to restart the beams in the machine.

A post-mortem analysis of this event was conducted at CERN in April 2024 with all the stakeholders to understand the root causes of this unlikely event. One of the lessons learned from this experience is that in such a situation, additional vacuum pumping groups must be prepared in advance to be rapidly installed in case of unexpected degassing during the natural warm-up process.

The CERN mechanical group concluded that based on present results and observations, it is reasonable to assume that there were linear imperfections that acted as a stress concentrator associated to extensive presence of δ-ferrite. At low temperature, ferrite has an embrittling effect and significantly reduces fracture toughness. This, associated to the stress field at this specific position led to crack initiation and final breakdown with peak of stress due to the rise of pressure (warming up of liquid helium). The crack propagation has been probably fast (limited ductility associated to the rupture) also due to the dual microstructure.

A set of recommendations were consequently issued to mitigate this risk in future and a global consolidation on all the remaining inner triplet edge-welded bellows will be addressed during the next LHC long shutdown 3 between 2027 and 2029.

Acknowledgments
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