

THE HISTORY OF VACUUM REGULATION TECHNOLOGY

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An inordinate amount of time, money and anguish has been invested in changing the ways that vacuum is controlled in milking machines. These extraordinary efforts have not resulted in a commensurate improvement in milking performance. There are two fundamental methods of influencing the vacuum in the milking machine: 1) a device to regulate 'system' vacuum, usually located near the receiver and 2) design and configuration of system components to reduce the vacuum difference between the regulated system vacuum and the vacuum at the teat end. The 'system' regulation devices are the primary emphasis in this paper but the influence of components and design will also be covered to put these two contributions to milking vacuum stability in perspective.

System regulation devices control the vacuum at a point downstream (in the direction of airflow) of the receiver. This control strategy tragically, CANNOT have any influence on the major causes of vacuum drop between the milkline and the milking unit and vacuum stability at the teat end, namely (in approximate order of significance):

- Vacuum drop in the long milk tube and the associated vacuum fluctuations caused by slugs of milk in the tube and intermittent air admission to the milking unit.
- Vacuum drop and vacuum fluctuations produced in the short milk tube due to milk slugs.
- Vacuum fluctuations at the teat end caused by the opening and closing of the liner
- Slugging in the milkline

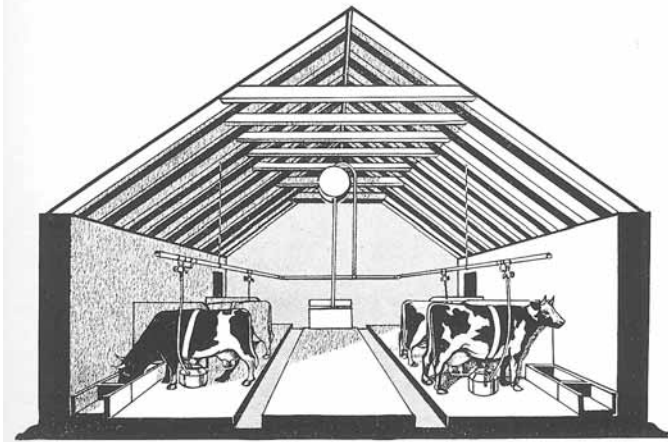
The vacuum measurement of most interest to the cow and her teats is the average vacuum in the claw during milking. The only legitimate function of most vacuum regulators is to provide a relatively stable reference vacuum in the receiver. If the milkline is designed correctly this same vacuum will also be supplied to the entire length of the milkline. The milkline vacuum together with knowledge of the relationship between milk flow rate and the milkline-claw vacuum difference will allow the competent evaluator to adjust the regulator vacuum to achieve the desired average claw vacuum for the majority of the time that milking units are attached to cows. As we will see, the history of vacuum regulation has shown an improvement receiver vacuum stability but the history of vacuum stability at the "business end" of the cow, her teat ends, has not progressed in this same orderly manner.

The Beginning of Recorded Machine Milking Time

This brief history of vacuum regulation is taken from the well researched and entertaining works by Hall (1959 and 1977) and Dodd and Hall (1992). Milking machines were first introduced in the late 1800's. It is presumed that the vacuum was set by trial and error to arrive at a vacuum level that worked reasonably well.

The first successful commercial milking machine the, Murchland machine, illustrated here, came on to the English the market in 1889. This machine used vacuum rather than pressure developed

by mechanically squeezing teats and won the Royal Agricultural Society of England (RASE) prize that year. The vacuum applied to the teat was continuous and the teat cups were specifically designed to keep the teat surrounded with milk. This machine, developed by a plumber, used a hand operated vacuum pump to maintain a vacuum of 37 kPa (11" Hg) using a water column as the regulation device. This vacuum control strategy has a great deal of merit in that there are no moving parts.



Dodd and Hall (1992) introduce an interesting sociological note in that the advertising for this machine states that the machine could be "powered" by one boy while the skilled task of operating two or three units each should be entrusted to up to three girls. The teat end vacuum in this machine was probably comparable to machines of today as long as the boy minded his business and was not distracted by the girls and the girls were "careful operators" (see ASAE S518 for details). A water column is an accurate and effective way to control vacuum and the bucket arrangement would have eliminated the major source of vacuum changes, those introduced by a long milk tube.

The next machine to win the RASE prize was the Nicholson and Gray machine in 1891. This machine used a nominal vacuum level of 45 kPa (15 "Hg). Thus began the pendulum swing of recommended milking vacuum over this same range that has continued until today. The method of vacuum regulation in the milking machines used in the early 1900's is not well documented but weighted or spring devices were probably the main control technologies.

Sources of Vacuum Fluctuation

The 'system' vacuum in a milking machine is the result of the instantaneous balance of air being admitted into the machine and the air being removed from the machine. The "planned" or "normal" air admission include sources that are relatively steady, such as claw air vent and system leaks, as well as those that are unsteady and cyclic such as the air used by pulsators. There may also be planned air admission that does not occur on a steady or regular cyclic basis such as the air used by vacuum operated detachers. In addition to these planned air admissions, "unplanned" air admission occurs when milking units are attached, detached and when units falloff or in the most extreme case, when a milk hose is removed from an inlet on the milkline.

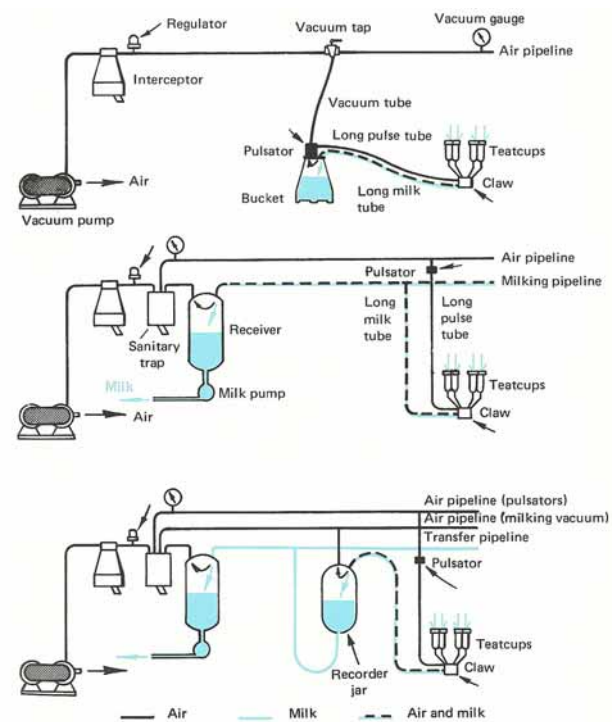
A milking system behaves as a low-pass filter towards air admission disturbances (Tan and Reinemann, 1996). Air is a compressible fluid, and as such, provides a considerable amount of 'damping' of the vacuum changes that result when momentary imbalances between air admission and air extraction occur. You can think of the air inside the milking machine as a partly coiled spring that absorbs some of the pressure variation produced by air admission. The rate of vacuum change in the receiver (and at the vacuum sensing point) typically less than 30 kPa/s

during the extreme event of a milk hose removed from a milk inlet during a dry test (Reinemann et al., 2001).

The difference between system (or receiver) vacuum and the teat-end vacuum are mainly the result of movement of milk through the short milk tube, claw, long milk tube, and milkline. Milk is an incompressible fluid with a density about 1000 times greater than that of air and the flow velocity of milk in the short milk tube can be considerably faster than the flow velocity of air in the milkline. While air acts as a damper to reduce vacuum changes and the rate of vacuum change, milk slugging propagates high-frequency vacuum fluctuations in the wetted part of the milking machine (Tan and Reinemann, 1996). As a result, the vacuum changes associated with slugs of milk moving through milk tubes are up to 10 times larger and 400 times faster than the changes than can be sensed by the vacuum regulator (Reinemann et al, 2001).

Because the regulator cannot sense the major contributions to vacuum change at the teat end, various system components and designs have been implemented over the history of milking machine development to reduce the difference between vacuum at the teat end and vacuum at the regulator sensing point. These include:

- Separating milk and air flow near the cow using a specially designed claw or a bucket or weigh jar milking system. The nearer to the teat end the separation point occurs the greater reduction in vacuum change due to milk slugging.
- Reducing the lift height from the claw to the point of regulated vacuum, ranging from of up to +2 meters for high-level pipeline systems, +1 meter for mid-level and weigh jar systems, -1 meter for low level pipeline systems, and -2 meters or more for very-low-level or 'basement' pipeline systems.
- Devices to reduce teat end vacuum during periods of low milk flow.
- Devices to reduce the amount of 'unplanned' air admission, such as shutoff valves on claws or teatcups.
- Increasing the diameter of the short milk tube, long milk tube, and milk line.

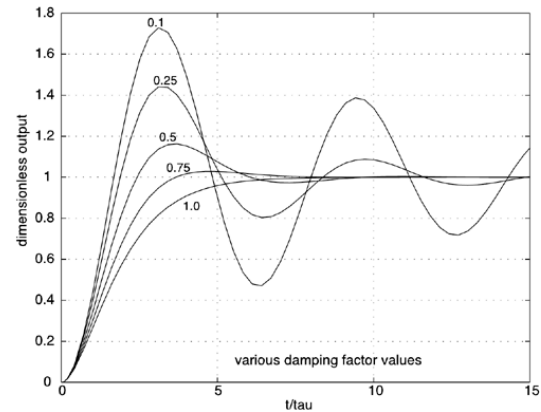


Control Theory

The vacuum in the dry parts of the milking machine behaves as a damped second order system. Each milking machine will have a natural frequency that depends on the system volume and configuration and vacuum pump capacity (Tan, 1992). The response of a damped second order system will be:

- Critically damped, (damping factor = 1) responding to a change in vacuum without over-shoot or under-shoot in the minimum amount of time,

- Over damped, (damping factor >1): responding without over- or under-shoot but will take longer to return to the set point than a critically damped system,
- Under damped, (damping factor <1): oscillating for one or more cycles producing some over- and/or under-shoot but will eventually stabilizing, or
- Unstable: a small disturbance will cause the system to continue to oscillate indefinitely and oscillations may amplify.



The period of oscillation is the time between successive peaks. The overshoot is the difference between the first peak and the new steady state value and is usually expressed as the overshoot ratio. The decay ratio (ratio of the second overshoot peak to the first overshoot peak) is a measure of how rapidly the oscillations are decreasing (Bequette, 2002).

The damping factor is influenced by the system design as well as the amount of damping in the regulation device itself.

The sensitivity of regulation is a measure of the amount of vacuum change required for the regulator to react. A more sensitive regulation system will usually result in a narrower band of vacuum fluctuation because it will respond sooner to a large change in vacuum. However, a regulation system that is overly sensitive will respond to small vacuum changes that are of no consequence. The sensitivity of vacuum control depends both on the sensitivity of the regulator (a fixed value for conventional regulators and a selectable value for VFD's) as well as the ratio of the vacuum change at the vacuum sensing point relative to the vacuum change at the receiver (measured in the NMC vacuum test procedures). A system with the regulator mounted on a long, undersized branched line will lack sensitivity because the regulator cannot 'see' the vacuum changes in the receiver. It is common for the system vacuum to fluctuate with the cyclic air admission caused by firing of pulsator banks. A regulation system that is too sensitive and under-damped may increase this vacuum fluctuation. Air-damping can be also applied to the milking system to reduce these fluctuations (Patoch, et al., 1996).

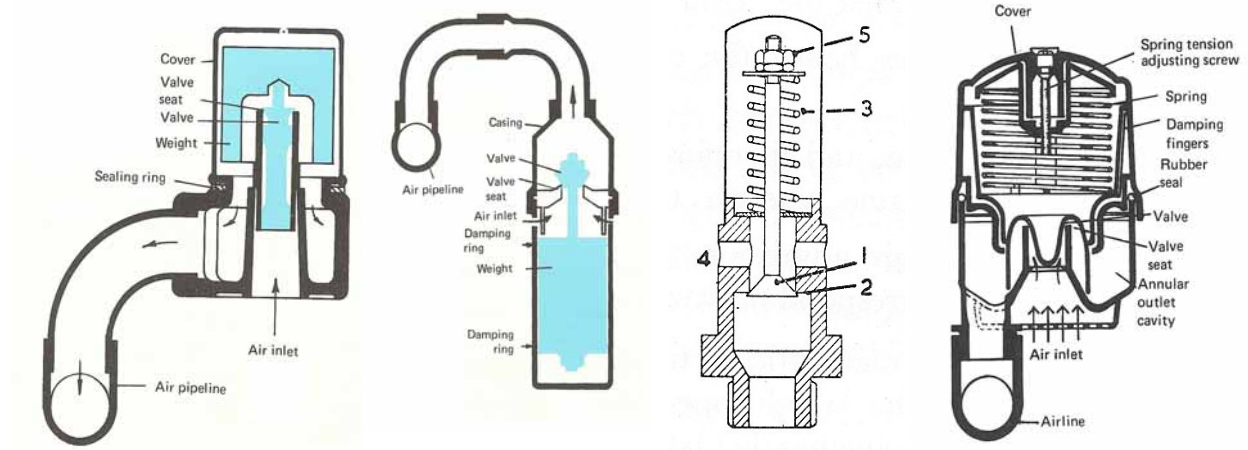
The response rate is a measure of how fast the system can respond to a change in vacuum. This is a fixed value for conventional regulation system and will depend on the pump capacity and system volume. The response rate is a selectable parameter for VFD controlled systems. A fast response rate will result in more rapid recovery, but will also tend to increase the amount of overshoot. VSD controllers use proportional integral control logic. This is a complicated strategy to adjust the response to hit the target without overshooting. In general if overshoot is eliminated the system becomes over-damped and will take longer to arrive back at the vacuum set point.

"Conventional" Regulators: Push Me, Pull You, and Admit Lots of Air

This review of vacuum regulator development and illustrations are taken from the work of Hall (1959), Akam (1977) and Akam and Spencer (1992). The most common form of regulating system vacuum over the past 100+ years has relied on a force balance between the partial

vacuum produced inside the milking machine and the resisting force of a weight, or spring. The vacuum pump runs at a constant speed with the amount of air removed remaining relatively constant at the maximum expected capacity for all use scenarios (there is some variation in air moved depending on the vacuum at the pump inlet). If more air is removed than admitted the system vacuum will rise and the control valve will open to increase the amount of air admitted through the regulator.

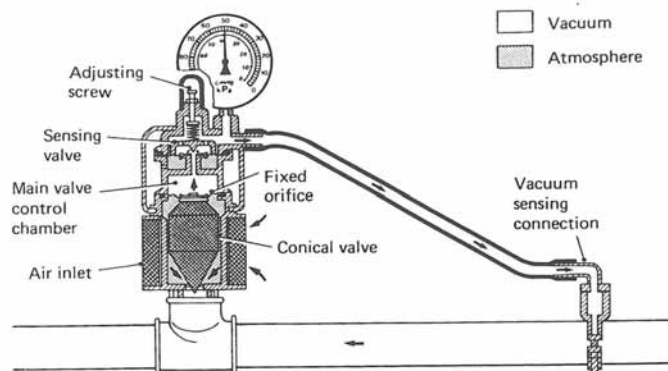
Weighted regulators use a 'dead weight' or a weight mounted on a lever system. The force of the weight acting to close the control valve is balance by the force of the system vacuum acting to open it. The rapid movement of the valve stem or weight may be impeded by a damping mechanism.



Spring actuated regulators use the same principle as weighted regulators except that the closing force on the control valve is supplied by a spring. The tension of the spring is adjusted by changing the length of the fully extended spring, usually with a screw-type adjusting mechanism. Spring actuated regulators may be damped using an oil fill reservoir or other mechanism.

Early designs for spring and weighted regulators sensed vacuum at the same point at which air was admitted. This results in inaccuracies of sensing the 'true' vacuum caused by the high velocity of air at the sensing point decreasing the sensitivity and response rate of the regulator.

Modern servo-operated regulators use a feedback system consisting of a sensing element and a mechanical amplification system. A small control valve regulates the movement of a much larger air inlet valve. Some sense vacuum at the point of air admission and some use a remote sensing point. These devices are a more sophisticated version of spring type regulators as the vacuum level is controlled by varying the force of a spring attached to the sensing element. The sensitivity and response rate are improved by using



mechanical amplification techniques and by locating the sensing point upstream from the air admission point.

Variable Frequency Drives

Variable Frequency Drive (VFD) controllers applied to vacuum pumps introduced a fundamentally new paradigm to vacuum control at about the 100 year anniversary of the mechanical milking machine. Rather than adjusting the amount of air being admitted to the milking machine, the VFD adjusts the amount of air being removed from the milking machine (Guo, et al., 1991). If more air is being removed than admitted, system vacuum will rise and the VFD system responds by decreasing vacuum pump speed to remove less air. VFD controlled systems reduce the energy used by the milking system because the vacuum pump must only remove the air that has been admitted to the system rather than the maximum expected instantaneous air admission at all times.

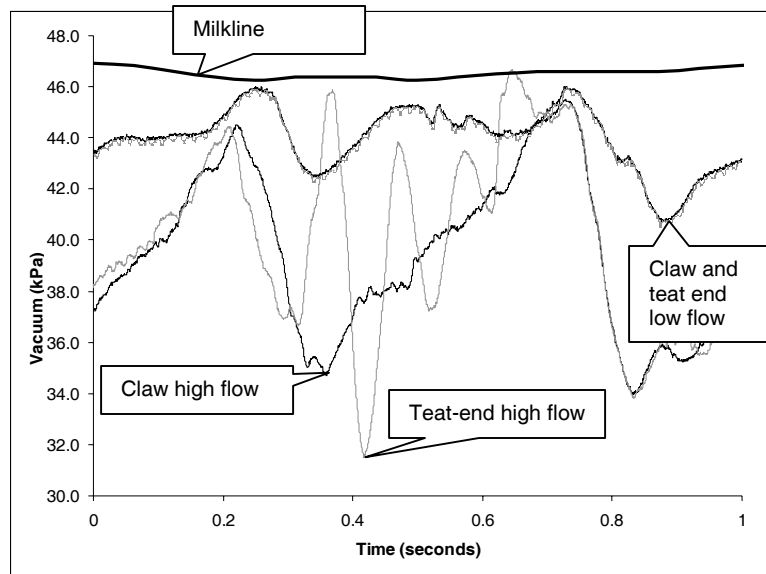
Historical Perspective on Vacuum Control

While there has been a steady improvement in the ability of vacuum regulators to maintain system vacuum at a steady level, the history of milking system configurations has not followed this same progression. Early milking machines had relatively small internal volume, small vacuum pumps and weighted or spring actuated regulators and milked cows with somewhat lower peak flow rates than those of today. It is conceivable that these system components were fairly well matched and that system vacuum was fairly stable. These early machines typically used bucket milkers and small diameter short milk tubes. The vacuum changes due to lift and slugging in the long milk tube were not present. The teat end vacuum was probably comparable to modern machines.

Increasing vacuum pump capacity probably created the need to increase the damping of vacuum controllers to maintain system stability and reduce over- and under-shoot. The move from bucket to pipeline systems added a source of large vacuum changes at the teat end created by milk moving through the long milk tube, especially in high level pipeline systems. Vacuum regulators were oblivious to this situation as they could not sense these vacuum changes and therefore could have no influence on them. It was, however, during this time that servo-controlled regulators were introduced, which improved the sensitivity of vacuum regulation.

The widespread adoption of low-level pipeline systems in milking parlors improved vacuum stability at the teat end and the move to very-low-level pipelines in basement parlors further reduced the influence of milk flow rate on teat-end vacuum. Increasing the diameter of short milk tubes has decreased the vacuum changes introduced between the claw and teat end and increasing the diameter of long milk tubes has moderately decreased the vacuum changes introduced between the milkline and claw. None of these developments have produced a substantial change in the stability of system vacuum.

The relative contributions to vacuum change at the teat end for a modern milking machine are illustrated in the following figure. The heavy line across the top is the typical vacuum drop in the milkline caused by air admission from a unit attachment. Claw vacuum and teat-end vacuum for both low milk flow and high milk flow rates are also shown. At low milk flow rates the main contribution to vacuum change at the teat end are caused by moving milk through the long milk tube. At high flow rates the influence of the long milk tube increases and substantial difference between the claw and teat end appear as milk slugs begin to appear in the short milk tube.



If VFD controllers are adjusted properly they can meet or exceed the vacuum stability of conventional regulators (Ludington and Southwick, 1998, Pazzona, et al., 2003). Remember that the performance target is receiver vacuum within ± 2 kPa (0.6 “Hg) of the vacuum set point during normal milking. Adjusting a VFD controller is more difficult than setting a conventional vacuum regulator. In order for the VFD to function properly its user selectable sensitivity and response rate must be matched to the milking system (Ludington and Southwick, 1998). Noise levels are typically 12 dB to 24 dB lower and energy used 50% to 80% lower than for systems with constant speed vacuum pumps (Pazzona, et al., 2003). The current drawn by VFD controlled vacuum pumps is considerably less than constant speed pumps so that the neutral-to-earth or 'stray' voltage produced will also be considerably less. The complex switching of VFD units does produce some waveform distortion, but the relatively low frequencies of these harmonic components do not substantially change animal sensitivity to contact voltage or current and appropriate filtering will eliminate interference with other electrical equipment. VFD controllers reduce the starting current of large electric motors, which may be a significant advantage when operated on some rural power distribution systems and reduces the magnitude of momentary motor starting neutral voltages.

The most recent development in machine milking, robotic milking machines, have provided an excellent large scale field study on the influence of vacuum fluctuations at the teat end. The very long “short’ milk tubes in all robotic milking machines result in the largest cyclic vacuum fluctuations at the teat produced by any milking machine in the last 100 years, yet numerous studies have shown no measurable difference in somatic cell counts of cows milking robotically versus those milking with ‘conventional’ milking machines. Probably because the widespread use of more stable clusters, larger-bore short milk tubes and larger claw bowls has already reduced the potential gain from eliminating the claw in many milking systems (Mein et al, 2004).

Effect of Vacuum level and Vacuum stability on Milking Performance.

Research and field experience has underscored the fact that vacuum stability in modern milking machines is a relatively unimportant factor in the success of the milking process. Woolford

reported in his (1995) literature review that the considerable effort expended on improving vacuum stability in receivers and milklines from 1985 to 1995 had been misdirected. By 2003 the preoccupation with vacuum stability in receivers and milklines had been moderated only somewhat (Reinemann, et al., 2003).

Average teat-end vacuum: Rasmussen and Madsen (2000) reported that milking at low vacuum (26 to 30 kPa average at the teat end compared to high vacuum of 33 to 39 kPa) increased machine-on time and frequency of liner slip, had no influence on teat condition and udder health while the milk yield of high yielding, slow milking cows was reduced by 5%. The main milking performance problems introduced by low teat-end vacuum are the associated increase in liner slips and unit fall-offs which is primarily a disruption to the milking work routine. Machine-on times will increase somewhat with lower teat-end vacuum but this is seldom a limiting factor in the milking routine. Milking at high vacuum has been shown to decrease machine-on time slightly (about 15 seconds per inch of mercury, Reinemann, et al., 2001a; and many others) increase teat congestion, (Hamman et al., 1993), increase the number of teat ends open after milking and the amount of time for teat ends to close after milking, increase teat end hyperkeratosis (Rasmussen et al 1993, Mein et al, 2003, and others) and increase strip yields (Reinemann et al, 2001a; and many others). The pendulum swing of fashionable milking vacuum continues to swing back and forth but the recommendation in the ISO standard of an average claw vacuum of 32 to 40 kPa during the peak milk flow rate as a good compromise that ensures that most animals will be milked quickly, gently and completely remains valid and is supported by research and field experience over the history of the mechanical milking machine.

Vacuum Fluctuations: Mein et al, (2004) concluded that most mastitis infections are caused by factors other than the milking machine and correlations between unstable milkline or receiver vacuum with increased mastitis are likely to be associative rather than cause-effect relationships. Air speeds greater than 2 m/s up the short milk tube may assist bacterial penetration into or through the teat canal but vacuum fluctuations in the milkline or receiver and produced by liner movement are much too slow to generate these speeds and thus vacuum regulators do not play a role in bacteria transport. Furthermore, Rasmussen et al., (1994) reported that 99% of reverse pressure gradients across the teat canal occurred during manual teat handling (54%), attachment of the milking unit (29%), and detachment of the milking unit (26%), none of which can be influenced by vacuum regulation.

Conclusion

While the sensitivity and response rate of vacuum regulators has improved somewhat over the past century their influence on teat end vacuum has remained relatively small and the response rates of even the most modern of these types of device are still much slower than the rates of vacuum change in the claw. It has been speculated that the reason we have spent so much time looking at vacuum stability in the receiver because it is a relatively easy quantity to measure and control, not because it is of critical importance to milking.

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