COOLING EFFICIENCY IN FURNACE DESIGN

EFICIENCIA DE LA REFRIGERACIÓN EN EL DISEÑO DE HORNOS

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ABSTRACT: During melting, reduction or thermal treatment of a steel charge, the input of energy (either chemical or electrical) is indispensable to guarantee the viability of the process. Under these circumstances, it will be reasonable to design the furnace lining in such a way that heat loss through the walls is minimized. Nevertheless, it can be proved that, for some situations, it is more efficient to withdraw as much heat as possible from the walls than trying to thermally isolate the system. The work presents recommendations for the design of walls and cooling systems in furnaces obtained by quantitative analysis of temperatures reached in specific locations of the furnace using the nodal wear model. The analysis indicates that the wear process of the lining may be controlled if all the elements that intervene in the process are known.

KEYWORDS: Metallurgy, furnaces, heat loss, lining, wear.

RESUMEN: Durante la fusión, la reducción o el tratamiento térmico de una carga de acero, es indispensable suministrar energía (ya sea química o eléctrica) para garantizar la viabilidad del proceso. Bajo estas circunstancias será razonable diseñar el recubrimiento de los hornos de forma que la pérdida de calor a través de las paredes sea mínima. Sin embargo, se puede demostrar que, para algunas situaciones, es más eficiente retirar la mayor cantidad de calor posible de las paredes que intentar aislar térmicamente el sistema. El trabajo presenta recomendaciones para el diseño de paredes y sistemas de refrigeración en hornos, obtenidas mediante el análisis cuantitativo de las temperaturas que se alcanzan en posiciones específicas del horno y usando el modelo de desgaste nodal. El análisis indica que el mecanismo de degradación del refractario puede ser controlado si se conocen todos los elementos que intervienen en el fenómeno.

PALABRAS CLAVE: Metalurgia, hornos, pérdida de calor, recubrimientos, desgaste.

1. INTRODUCTION

In previous works [1], the criteria to select the most suitable materials to design the lining of furnaces have been detailed, considering the following:

- Optimize the heat loss in the whole system by reducing heat flux through walls, wells and ceiling.
- Minimize the amount of heat stored in the lining, which is directly proportional to its density and specific heat capacity.
- Minimize the wear or degradation of the materials used.

One of the conclusions of this analysis is that the degradation suffered by the furnace lining, may also be a variable with beneficial consequences for the process, as long as both the speed and the mechanisms acting during the degradation are controlled in a precise manner.

Besides these concepts, the work presents theories in order to distinguish if adding thermal insulator to the refractory is beneficial to the process or if external cooling of the materials in contact with corrosive fluids should be a generalized practice and recommended in any situation [2-5].

For most of the works published, in which laboratory results of the interaction between a refractory or a ceramic in contact with a chemically aggressive fluid are interpreted [6], though considered interesting from a scientific point of view, they have very few repercussions and applications in the technological field, which is an example of the growing disparity in the interpretation of basic scientific concepts resulting, in some cases, in different industrial applications that are conceptually contradictory between themselves. This has resulted in the advancement of the last 50 years to be questioned (along with all the published texts), arguing that the developments and calculations previously presented were only valid for that period of time, and denying the capacity to accumulate technical knowledge. Consequently, it is imperative to formulate a universal law for the behavior of the furnace refractory that explains all the observed results, in order to achieve an adequate technical and scientific level.

Moreover, a growing skepticism has manifested inside industries dedicated to technology and engineering, towards laboratory tests and research on the wear of materials since these results may not be complete or adequate to evaluate the performance of a certain refractory in an industrial application, when designing a furnace lining. In response to these contradictions, over the last years and working together with the industry, the Nodal Wear Model (NWM) has been developed, resulting in theoretical formulations and basic generalizations, which have clear technological applications in the design of furnaces [2,7-9], as models representing the 3-dimensional phenomenon taking place inside the hearth may be difficult to analyze [10].

2. COOLING AND INSULATING SYSTEMS

It may seem as a contradiction (especially at this moment in time), that with very high prices of energy and environmental problems due to the presence of NO_x, CO_2 and SO_2 in the atmosphere, to seek a lower energetic efficiency in a process. Thus, it seems unreasonable to propose the removal of insulating layer in contact with the steel structure - shell of the furnace and, furthermore, promote the extraction of heat at the lining using cooling fluids (air or water). The design of a furnace (DE-Furnace) is a function that depends on three variables: operative parameters (OP), characteristics of the refractories used in the lining (RE) and geometry and external limit conditions for the furnace (GE-LC); which in turn, depend on a large number of variables connected to the fluids and materials properties used in the furnace [2-4]:

$$\text{DE-Furnace} = F\,(\text{OP; RE; GE-LC}) \quad (1)$$

The final numerical value the OP, RE and GE-LC variables may have, are connected in some degree to the temperature surrounding each of the most important zones of the installation. Consequently, it is fundamental for the designer to have information as precise as possible of the thermal profile that the whole installation develops both at the beginning as at the end of the operation life cycle.

As shown in Figures 1, 2 and 3, if the thermal 2D profiles of a common lining are analyzed, four regions may be clearly distinguished:

1. Constant temperature zone T_F^∞ produced by the fluid region, in which the temperature may be experimentally determined. It is common to give this zone a constant value because, though the thermal conductivity λ ($W \cdot m^{-1} \cdot K^{-1}$) is not elevated, it has a convective flux and radiant heat high enough for thermal gradients to be disregarded.

2. Thermal limit layer $\delta(T)$ commonly with a thickness of a few millimeters, but with the possibility of considerable temperature differences in its interior [11].

3. Refractory wall in which the temperature drop is a function of the thermal conductivity of the

material λ ($W \cdot m^{-1} \cdot K^{-1}$). Usually, and for the purpose of minimizing heat loss, a dense material is selected (work refractory) to be in contact with the corrosive fluid, as well as another one with insulating characteristics to be in contact with the exterior steel shell [2-4].

4. Furnace exterior zone in contact with the environment that may be cooled with air or water [4].

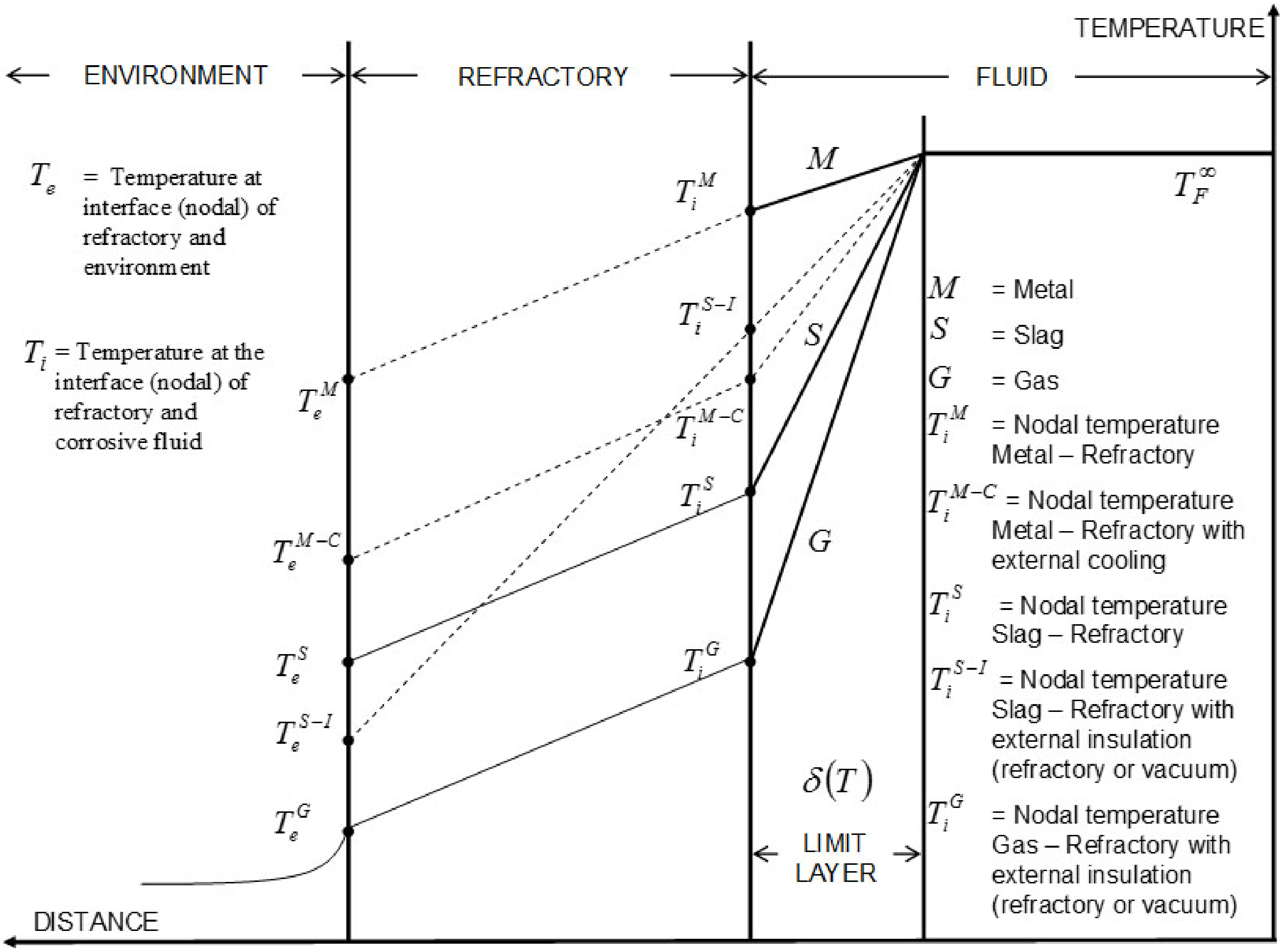

Figure 1. 2D temperature distribution along environment-refractory-fluid (metal, slag or gas) interfaces. Effect of cooling, insulation and physical-chemical nature of the melt.

A fifth region that corresponds to the steel plate structure (and that provides the required stiffness to the system) has been excluded. Nodal temperatures at this region in contact with the environment T_e and the loads and stresses the structure suffers, are the specifications the selected steel must fulfill in order to avoid creep straining (plastic deformation of materials, consequence of mechanical stresses combined with high temperature).

Even though the insulating materials used industrially show a thermal conductivity between 0.50 and 0.10 $W \cdot m^{-1} \cdot K^{-1}$, it is important to point out that with high vacuum layers / chambers (10^{-4} mm of Hg), values as low as 0.01 $W \cdot m^{-1} \cdot K^{-1}$ (Figure 2) may be reached. If the system does not show mechanisms of physical, chemical or mechanical degradation by the action of corrosive fluids (it practically behaves as an adiabatic system), the use of the aforementioned vacuum layer technology may be very effective, though complicated to implement.

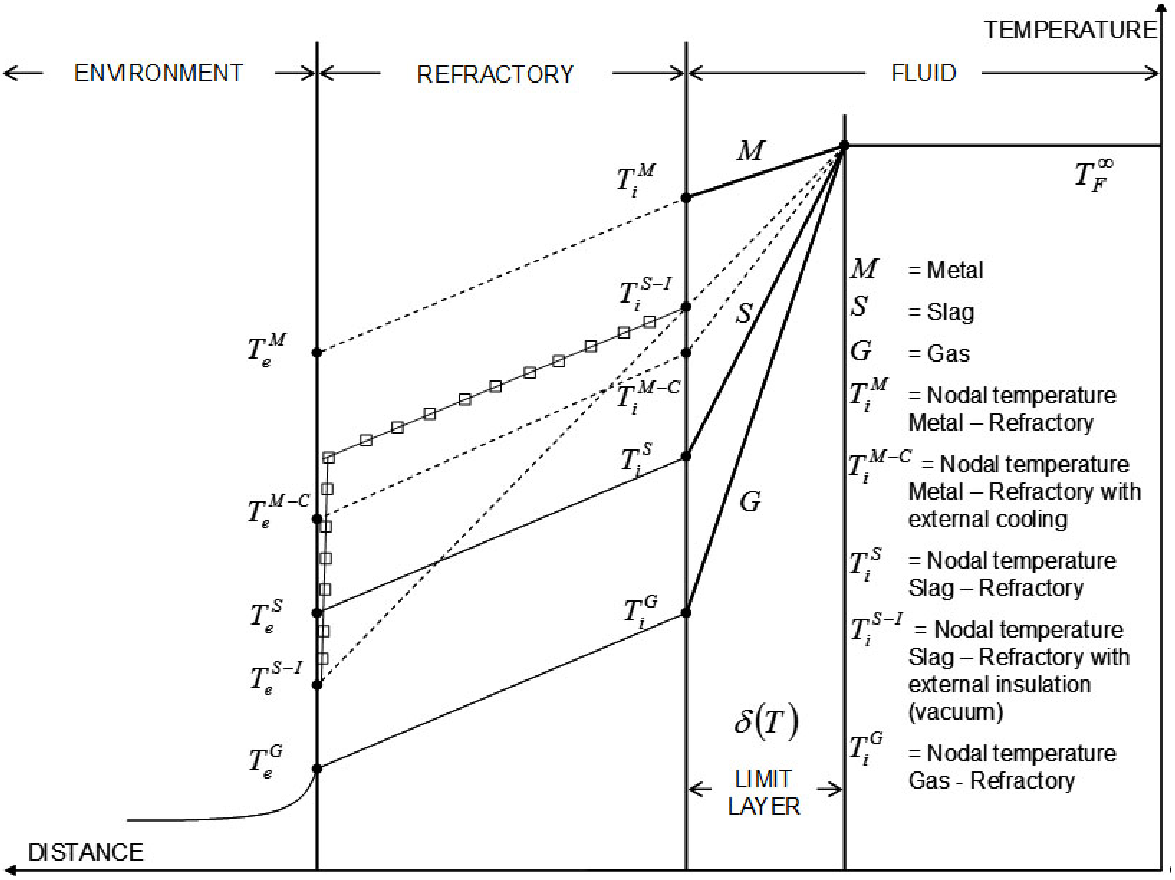

Figure 2. 2D temperature distribution along environment-refractory-fluid (metal, slag or gas) interfaces. More detailed characteristics than in Figure 1, along with the effect of insulating with vacuum and the consequences of the physical-chemical nature of the corrosive fluids.

It may be considered, that the temperatures, at nodes in contact with aggressive fluids T_i , diminish both by the effect of the degradation of the material, as well as by the existence of external cooling. In contrast, nodal temperature T_i , increases either when a zone/chamber of external vacuum is provided, or when a layer of insulator in contact with a dense refractory is used (Figures 2 and 3).

Finally, it must be considered that both the nodal temperatures T_i along the working refractory, and the aggressive fluid interface, as well as those located at points in contact with the environment T_e (Figure 1), or even the ones in contact with lining materials with different characteristics T_{i-l} (Figure 3), will not show constant values, and are a function of its position in the furnace. For a 2D model:

$$T_{i-l}, T_e \text{ and } \quad T_i = f(x,y) \qquad (2)$$

3. FURNACE DESIGN

The concepts previously developed, result in practical criteria that must be taken into account when designing or constructing furnaces, or its refractory linings. However, it is noteworthy, even today, that most of the criteria used in the design of high performance zones in furnaces (crucibles and domes), are being guided by data obtained by static and dynamic corrosion tests at laboratory level [12-14]. The failures in numerous occasions have been noticeable [15], though, a considerable number of users or consumers of these products, still defend the use of laboratory tests as the criterion to obtain data and select the most suitable materials in contact with corrosive environments [16].

The NWM, besides its capacity to quantitatively interpret the evolution of wear, is a very important tool when specifying the design of a wall, a well or a dome of a furnace. The fundamental hypothesis of this theory, which in a sense is obvious, is that the controlling magnitude of the physical or chemical degradation of the lining is proportional to the nodal temperature T_i (Figures 1, 2 and 3) and not to the temperature of the melt T_F^{∞} The industrial operating temperature T_F^{∞} and the one reached during laboratory tests may be the same, but this does not mean that nodal temperatures T_i in the laboratory are equivalent to industrial ones. In the same way, the temperature of zones from the cold side of the refractory in contact with the environment T_e are not equal to the temperature of the environment T_e^{∞}.

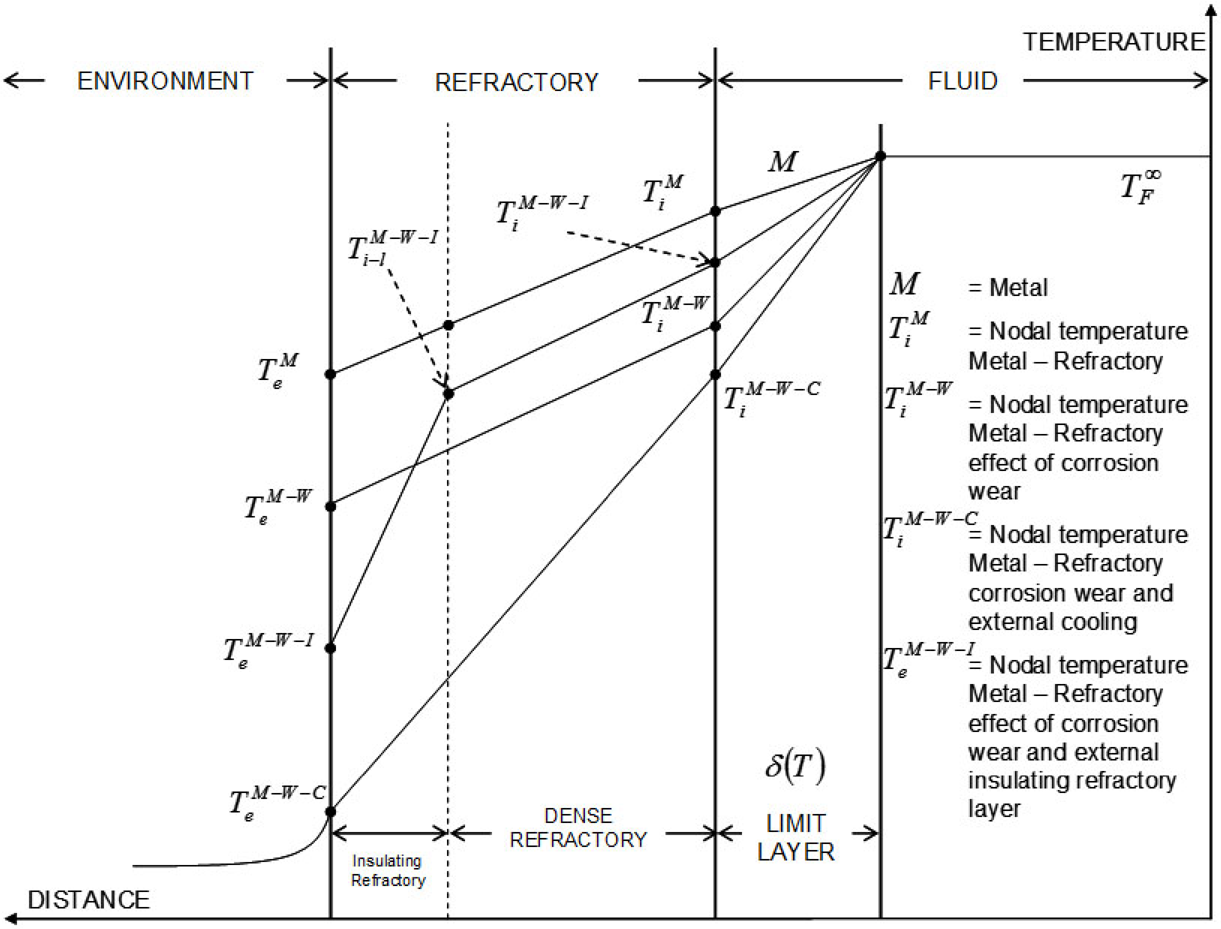

Figure 3. 2D temperature distribution along environment-insulating refractory-dense refractory-fluid (metallic) interfaces. Effect of the wear of the refractory, of the insulating refractory layer and of external cooling.

In the case of composite walls (a dense refractory combined with an insulating one) [3], it is important to use the NWM in order to simulate thermal conditions, and estimate the temperature at the insulator-work refractory interface T_{i-l} so it will not surpass the specifications of the insulator, becoming the origin of its degradation (loss of thermal and mechanical properties).

Finally, and insisting in the importance of T_i , T_{i-l} and T_e temperatures, in the design/construction of furnaces, the design conditions must produce nodal temperatures at zones in contact with the steel sheet T_e, that will not surpass the specifications of the material under constant load and temperature conditions, and in this way, prevent permanent deformations by creep mechanisms. In the cases where external cooling is achieved using water, like in some lids of electric furnaces (Figure 4), the temperature of the steel in contact with the cooling water T_e^{M-W-C} (Figure 3) must be low enough to prevent the activation of electrochemical corrosion wear processes of the carbon or stainless steel.

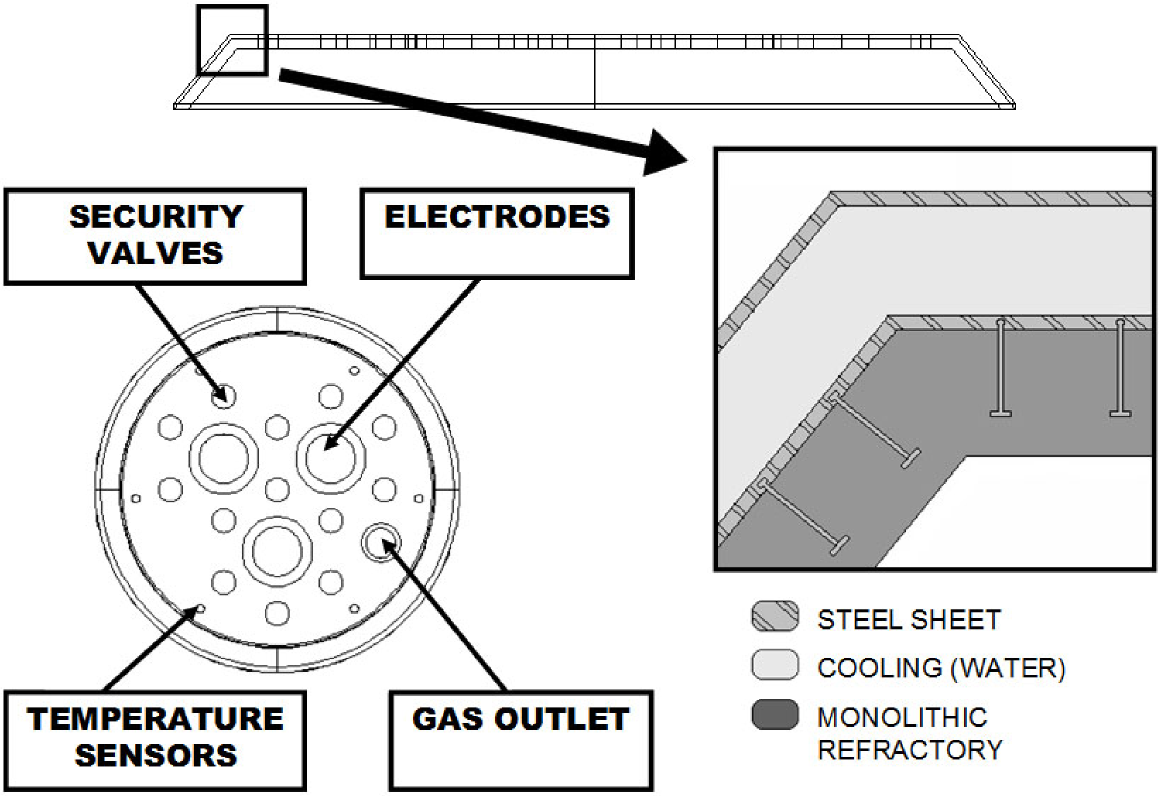

Figure 4. Scheme of a lid with cooling in an electric furnace

4. CONCLUSIONS

It is not always an advantage, from the operation and production management of an industrial installation, to reduce heat loss through certain sections of the furnace to a minimum. It is necessary to analyze the physical and chemical characteristics of the corrosive fluid and of the material most adequate to be in contact with it in order to protect the steel structure which provides stiffness to the furnace.

The corrosion of the refractory material in an industrial installation may cease to be a problem if the degradation mechanism is identified and its rate is regulated. For example, the design proposal may either be a zero-wear lining or one that promotes the controlled degradation of the refractory until it reaches total passivation of walls and well.

Both the behavior of the working materials as well as those of insulating layers that may be installed, or of the steels used as surrounding structures with cooling systems, are determined by the nodal temperatures that exist at the melt-refractory T_i, insulator-refractory T_{i-l} or refractory-environment T_e.

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