Thermal expansion under load of candidate material for MHD preheaters
by Alan Lester Halvorson

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Physics
Montana State University

Abstract:
In a coal-burning MHD (Magnetohydrodynamic) power plant, a regenerative air preheater will probably be used. To have the preheater lined with commercially available refractory materials is economically wise. The preheater environment places enormous thermal, mechanical, and chemical stresses on these materials. For this reason, candidate materials must be carefully tested. In this work, the thermal expansion under load and initial creep rates of candidate materials are examined. The system used for these measurements is discussed in detail. The data for chrome magnesite (Corhart Refractories, Type RFC) and magnesia alumina (Corhart, Type X317) are presented.

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Signature Alan L. Halvorson

Date May 19, 1980

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ABSTRACT

In a coal-burning MHD (Magnetohydrodynamic) power plant, a regenerative air preheater will probably be used. To have the preheater lined with commercially available refractory materials is economically wise. The preheater environment places enormous thermal, mechanical, and chemical stresses on these materials. For this reason, candidate materials must be carefully tested. In this work, the thermal expansion under load and initial creep rates of candidate materials are examined. The system used for these measurements is discussed in detail. The data for chrome magnesite (Corhart Refractories, Type RFG) and magnesia alumina (Corhart, Type X317) are presented.

CHAPTER 1

INTRODUCTION

With the price of oil continuing to rise, new sources of energy which are less expensive and more efficient are sought. In recent years, more and more researchers have turned their efforts to this problem.

Coal, which is an easily available and abundant resource, could help to supply our energy needs for many years.

One promising way of efficiently generating energy, using coal, is MHD (Magnetohydrodynamics). Magnetohydrodynamics has been around for many years. Patents dealing with MHD power generation started to appear around 1910. However, probably the first "real" MHD generator was built at AERL (Avco Everett Research Laboratory) in 1959 by R. Rosa and others.[1]

In a coal-fired MHD generator, a high temperature plasma is produced from the combustion of powdered coal. The electrical conductivity of the plasma is usually enhanced by seeding the slag with K_2CO_3 or K_2SO_4. The electrically charged gases move by expanding through a duct or channel which is surrounded by a magnet (superconducting usually) that produces a very strong field. According to Faraday's law of magnetic induction an electromotive force is generated by the flow of this conducting gas through the magnetic field. A Lorentz force acts on the charged particles causing a current to flow to an external load.

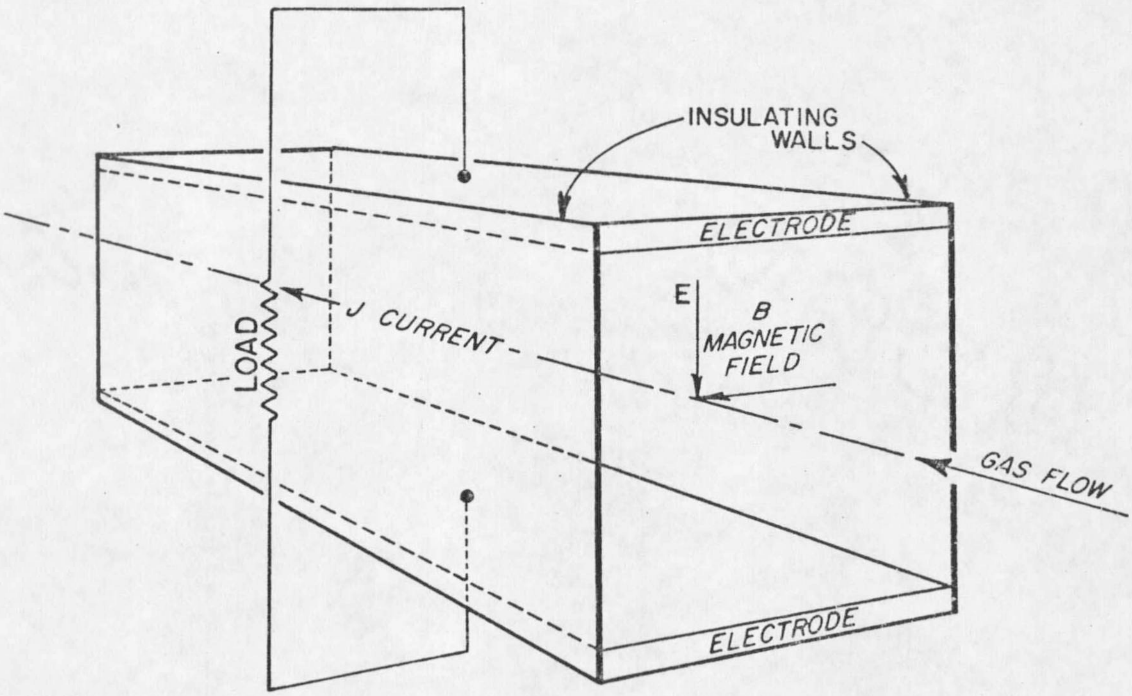
Figure 1 is a conceptual diagram of the current flow induced by the EMF in the MHD channel.[2] The current flows through an external load resistance to show schematically that it does useful work. The great advantage of an MHD generator is its simplicity -- it has no moving parts. R. Rosa thoroughly discusses the technical aspects of MHD in his book.

To be efficient, the MHD generator combustor must be at a high enough temperature to ionize sufficiently the seeded combustion products so that the plasma has the appropriate electrical conductivity as it passes through the generating channel. To achieve the required channel temperature, a regenerative air preheater, employing cored bricks of refractory material as the heat storage medium, is commonly used to preheat the air for coal combustion. A regenerative heater is a cyclic heat exchanger utilizing a heat storage material. During one half cycle, called the reheat cycle, the storage material is heated by the MHD combustion gases after they have passed through the channel. In the next half cycle, called the blowdown cycle, the storage material gives up its heat by conduction to the air being heated for coal combustion. This mode of operation is more efficient than separately firing the preheater.

Preheaters to be used with open-cycle power plants can be fired directly with the MHD channel exhaust or indirectly with a separate heat source. But in a closed cycle generator, energy released during

FIGURE 1

Conceptual diagram of a magnetohydrodynamic channel. Directions of the gas flow, magnetic field, and current density are shown.


INSULATING
WALLS
ELECTRODE
E
B
MAGNETIC
FIELD
J CURRENT
LOAD
GAS FLOW
ELECTRODE

CHANNEL

combustion is transfered in a heat exchanger to an electrically conducting gas or fluid which is permanently recycled through the generator.

A major concern with the use of preheaters is the severity of materials problems encountered. As mentioned earlier, the gases that flow through the channel are made more conductive by seeding. This seeding creates an environment very corrosive to the heat-storing firebrick of the preheater. In addition, there are enormous stresses, both thermal and mechanical, due to thermal cycling of the preheater and compressive loads from successive vertical layers of firebrick. Due to these problems, candidate preheater materials must be carefully tested.

An important physical parameter to be considered in determining a suitable refractory material for facility design is thermal expansion under load (TEUL). In addition, because yield strength and maximum dilation of materials changes with both load and thermal history, TEUL is a useful way to determine structural changes or damage.

It is the objective of this work to design and build an apparatus to measure the thermal behavior of potential preheated materials under MHD loads and temperatures. Measurements of pristine materials will then be compared to those exposed to a slagging environment to determine if any structural damage occurred.

CHAPTER II

BACKGROUND

"From ghoulies and ghosties, and long leggety beasties and things that go bump in the night, Good Lord deliver us" is an old Scottish prayer.[3] As structural members of buildings, coats of armor, etc., cooled in the evening, they were certainly among things that went "bump in the night". To visualize the consternation of our forefathers when such items suddenly emitted strange sounds is not difficult. The uses of thermal expansion in our daily lives are readily observable -- bimetal thermometers to control our heating and cooling systems, and hot water to "loosen" a stuck jar lid, to name two.

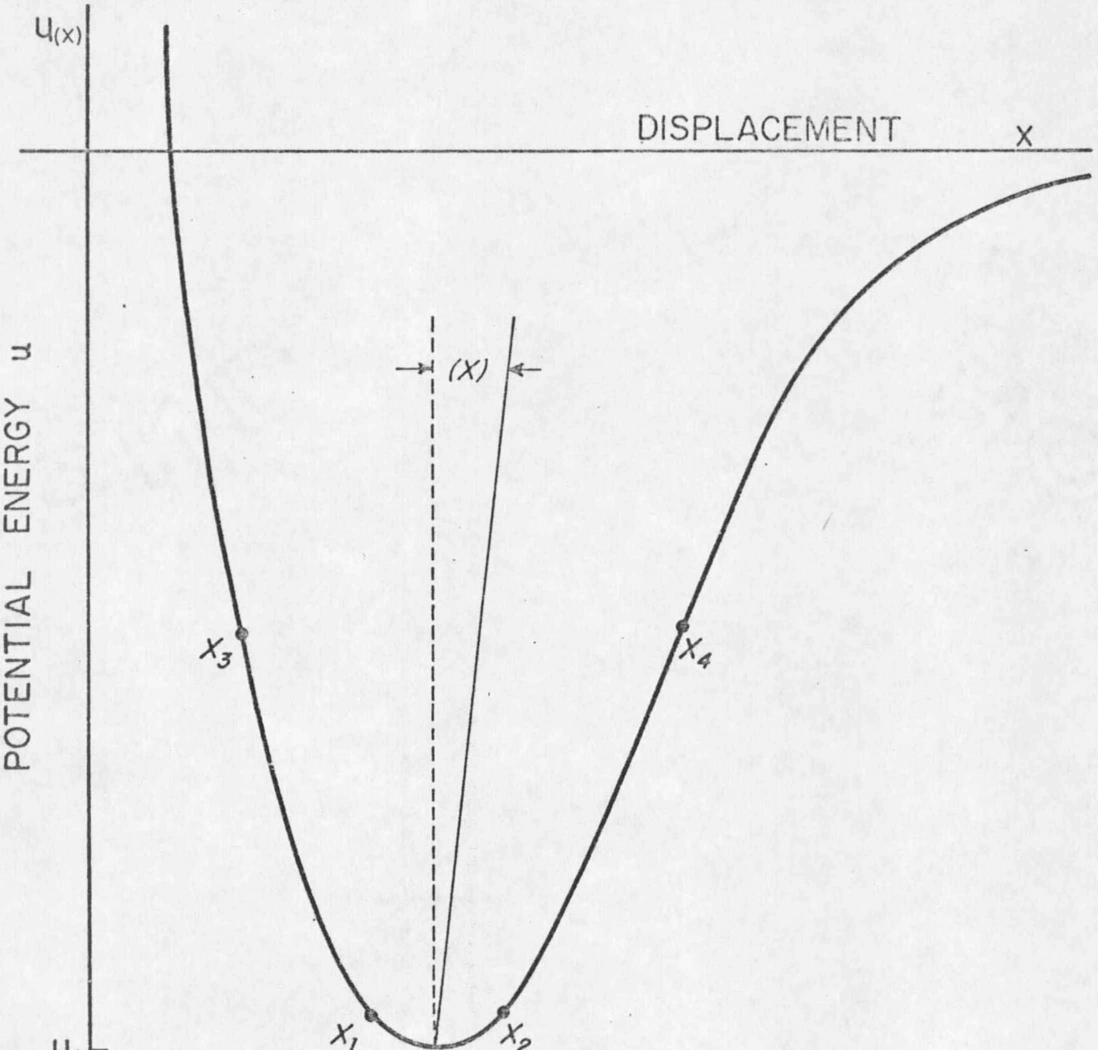
To understand thermal expansion, consider, as a reasonable model of a solid substance, a three dimensional array of atoms which are free to vibrate about their equilibrium positions. For simplicity their separation distance will be represented by a single configuration coordinate, x. Their potential energy is a function of the separation x and can be represented by a function U(x) (Figure 2). U(x) can be understood quantitatively with the help of a Taylor series expansion about the point x_o:

$$U(x) = U_o + \left(\frac{dU}{dx}\right)_{x_o}(x-x_o) + \frac{1}{2}\left(\frac{d^2U}{dx^2}\right)_{x_o}(x-x_o)^2 + \frac{1}{6}\left(\frac{d^3U}{dx^3}\right)_{x_o}(x-x_o)^3 + \ldots \qquad (1)$$

U_o is an arbitrary measure of the depth of the well and can be ignored or set to zero by a change of coordinates. Since x_o has been chosen to be a point where U(x) has a minimum, then $dU/dx = 0$ at x_o. By

FIGURE 2

Potential energy curve of a pair of atoms. As the thermal energy increases, the average separation of the atoms is somewhat greater, hence expansion.


U(x)
DISPLACEMENT
X
POTENTIAL ENERGY U
(X)
X3
X4
X1
X2
X0
U0

making a change of coordinates so $x_o = 0$, the remaining equation is essentially,

$$U(x) = Ax^2 + Bx^3 + \ldots \tag{2}$$

The first term in U(x) is a harmonic term and does not contribute to the expansion. In lowest order, the thermal expansion does not involve a symmetric term Cx^4 in U(x), but only the asymmetric term Bx^3.

Figure 2 is a graph of a typical anharmonic pair potential.[4] For a given temperature the atoms will have a certain thermal energy and will oscillate between positions x_1 and x_2. If the temperature is increased, the thermal energy increases, and the atoms now oscillate between positions x_3 and x_4. It is seen from the graph that the average displacement, <x>, has changed somewhat from its lower temperature value. Now the average separation of the atoms is somewhat farther apart, hence expansion results. As the amplitude of vibrations increases, due to an increase in temperature, it is the asymmetry of the potential well, due to the term in x^3, that causes the mean separation to increase.

If a bar of material is subjected to a succession of temperature changes that do not produce a change of state, its length will vary continuously with the temperature. It is found experimentally that the length ℓ can be represented by an expression of the form

$$\ell = \ell_o(1 + \alpha T + \beta T^2 + \gamma T^3 + \ldots) \tag{3}$$

where ℓ_o is the length at a reference temperature T=0 and α, β, γ and so on are constants. This is the equation used to fit a curve. Normally, it is sufficiently accurate to use the simple formula

$$\ell = \ell_o(1 + \alpha T) \tag{4}$$

The constant α, characteristic of the material, is called the coefficient of linear expansion and is used to calculate the change in any linear dimension of a solid, such as its length, width, or thickness. If Equation (4) is solved for α, it is seen that the coefficient of linear expansion of a substance can be described as the fractional change in length per degree rise in temperature.

To be more precise, the coefficient of linear expansion at the temperature T is defined by

$$\alpha_T = \frac{1}{\ell_o} \frac{d\ell}{dT} \tag{5}$$

and is exactly equal to the constant α in Equation (3). The mean coefficient of linear expansion between two temperatures T_1 and T_2 is

$$\alpha = \frac{\ell - \ell_o}{\ell_o} \frac{1}{(T_2 - T_1)} \tag{6}$$

Strictly speaking, the value of α in Equation (6) is temperature dependent because we have neglected the higher terms in Equation (3). For most applications this approximation is sufficient.

On a hot summer day the effect of thermal expansion would be readily apparent if not allowed for by the design engineer. In the design of any structure which is subject to changes in temperature, some provision must, in general, be made for expansion. Allowances should always be made in the construction of bridges, railroad tracks, highways, etc. The technological importance of accurate knowledge of thermal expansion is readily apparent when one considers the problems associated with high-performance engines, nuclear reactors, space-shuttle vehicles and the like.

Another form of deformation of a solid is due to stress. The deformation of a structure is expressed in terms of displacements resulting from applied loads. The deformation is the cumulative result of many small local strains, and the applied loads are associated with a complex pattern of local stresses.

The problem of determining the relation between applied loads and the overall displacements from local strains is the central task of the theories of strength of materials and elasticity. By considering a simple system where the properties are uniform throughout the structural system, the problem can be set forth adequately. The local state of a solid will certainly involve the stress, σ, the strain, ε, and the temperature. The normal force acting over a unit area of the cross section of a solid is called stress. If the forces applied to the ends of a bar are such that the bar is in compression, we have compressive stresses. When a compressive stress is applied to the bar, there is a length contraction. The normal strain, denoted by ε, is found by dividing the contraction by the original length. The strain is usually expressed in units of inches per inch and therefore is dimensionless.

Consider a one-dimensional solid system such as a bar subject to a compressive stress. For simple elastic structures it is observed that the ratio of stress to strain is independent of the stress. The ratio

$$E = \frac{\sigma}{\varepsilon} \tag{9}$$

is Young's modulus. For any particular substance E is nearly constant for a wide range of states.[5] If the same system is now heated so the change of temperature causes the sample to expand, the strain is governed by the expansion equation [Equation (6)].

If strain due to stress and changing temperature are now combined, the total strain is

$$\frac{\Delta \ell}{\ell_o} = -\frac{\sigma}{E} + \alpha(T_2 - T_1) \tag{10}$$

This equation, which gives the linear strain in terms of the normal stress and temperature is the simplest form of equation of state for a solid.

If the applied load or the temperature become sufficiently high the solid will begin to yield to the extreme conditions. This is the onset of creep. Although the objective of this work does not concern itself with extensive creep measurements, whenever feasible, we do take some initial creep data of a sample. Creep of materials may be defined as the time dependent strain of the solid under a constant load at a constant temperature. The three major reasons for creep are plastic deformation, changing crystalline phases, and grain