# Optimization of the magnetic core of a Linear Variable Differential Transducer

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***Abstract*— Research into materials and fuels for nuclear power reactors is carried out in so-called research reactors where various types of fuels and materials can be monitored online and in real time by in-core instruments. At the Halden reactor in Norway, online measurements such as cladding elongation, inner fuel rod pressure, fuel swelling, material creep and stress relaxation were based on Linear Variable Differential transducers (LVDT).**

**The magnetic core of the standard LVDT core is made of silicon iron, encapsulated by an Inconel 600 or AISI 316L tube for corrosion protection. In the present study, we consider FeCrAl as magnetic core material. This material, which is currently also being investigated as accident tolerant fuel cladding material, is corrosion resistant in the chemical environment of PWR or BWR reactors and therefore doesn't required an extra corrosion protection tube. As a result, the magnetic core diameter can be made larger, resulting in an increase of the LVDT sensitivity. In order to verify the various dependencies, the LVDT sensitivity was measured and compared to finite element calculations.**

**The sensitivity of an LVDT is influenced by the magnetic permeability of the magnetic core, as well as by eddy current losses in this magnetic core. When the temperature changes, the eddy current losses in the core also change, resulting in a slight change of the LVDT sensitivity. It is shown that this effect is reduced when using FeCrAl as magnetic core material, instead of SiFe. On the other hand, the change in magnetic permeability with temperature for FeCrAl is larger than for SiFe. The overall combined effect results in a higher dependence of sensitivity for the FeCrAl core.**

**Finally, using a solid magnetic core (without encapsulation) allows operation of the LVDT at higher gamma heating in the core of a reactor because of improved cooling by the surrounding water. This feature is relevant for operation in the Jules Horowitz Reactor, where the gamma heating in some locations can be up to 20 W/g.**

***Keywords* —LVDT, core, magnetic, eddy current**

## I. INTRODUCTION

In the Halden LVDT [1], the magnetic core is made out of Si(2.5%)Fe. The dimensions of this core are shown in Fig. 1. This core has a length of 24 mm and a diameter of 2 mm. Since SiFe is highly corrosive in high temperature water, it is encapsulated by a housing in Inconel 600 with an outer diameter of 3.3 mm and an inner diameter of 2.5 mm. The gap between the magnetic core and the housing (0.25 mm) is filled by helium at a pressure of 3 bar. The core housing fits inside the bore of the LVDT (inner diameter 4 mm), such that there is gap for water (or liquid metal) between the core holder and the LVDT of 0.35 mm. This gap is necessary for the correct cooling of the LVDT core.

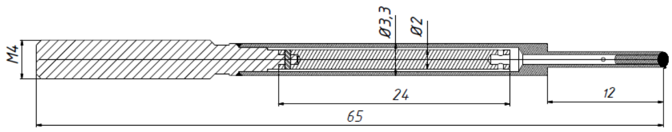


Fig. 1. LVDT core holder (Halden type)

In order to fabricate this type of core, some difficult steps are required:

1. Fabrication (by electrical wire discharge cutting of a 2 mm SiFe bolt out of a larger diameter (10-20 mm) bolt. This is a time consuming step.
2. Heat treatment of the SiFe core in order to obtain the required magnetic properties (involves heating in vacuum up to 850 °C).
3. Filling the gap region by a mixture of He (90 %) and Ar (10 %).
4. Seal welding the gas region.

Besides these mechanical steps, it can be recognized that the magnetic core assembly resembles very much a gamma thermometer (GT). Although He has a rather good thermal conductivity, the temperature of the magnetic core can nevertheless reach a high temperature at high gamma heating, such that the Curie point is reached. At this point, the LVDT stops functioning.

It is clear that if a material could be found which is both magnetic and corrosion resistant (in BWR or PWR conditions) that the design of the core could be simplified considerably because the core housing could be omitted in this case.

## II. DESIGN OF THE NEW MAGNETIC CORE

Such a material actually exists, namely FeCrAl. Kanthal is the trademark for a family of iron-chromium-aluminium (FeCrAl) alloys used in a wide range of resistance and high-temperature applications. Kanthal FeCrAl alloys consist of mainly iron, chromium (20–30%) and aluminium (4–7.5 %). The first Kanthal FeCrAl alloy was developed by Hans von Kantzow in Hallstahammar, Sweden. The alloys are known for their ability to withstand high temperatures and having intermediate electric resistance. As such, it is frequently used in heating elements. The trademark Kanthal is owned by Sandvik Intellectual Property AB. In recent years, FeCrAl is being investigated as cladding material for accident tolerant fuel rods in nuclear power reactors [2]. A FeCrAl rod (diameter 3.2 mm, length 200 mm) was ordered from Goodfellow. From Goodfellow's website, the following properties are retrieved:

<u>Composition</u> (%): Fe 72.8, Cr 22, Al 5 %, Y 0.1, Zr 0.1
<u>Physical properties</u>:
Density (g/cm$^3$): 7.22
Melting point (°C): 1380-1490
<u>Electrical properties</u>:
Electrical resistivity (µWcm): 134
Temperature coefficient (K$^{-1}$): 0.0001
<u>Thermal properties</u>:
Coefficient of thermal expansion @20-100 °C : 11.1 x10$^{-6}$ K$^{-1}$
Thermal conductivity @23 °C (W/mK): 16
<u>Magnetic properties</u>:
Curie temperature (°C): 600

The magnetic permeability could not be found. This is probably due to the fact that this material is normally not used for its magnetic properties.
Note that the electrical resistivity of FeCrAl (134 µWcm) is a factor 2.8 larger than that of Si(3%)Fe (47.2 µWcm). Because of this, eddy current generation within FeCrAl core will be even smaller than in SiFe and this should result in even better linearity.
The drawings of this prototype core are shown in Figs. 2,3,4.

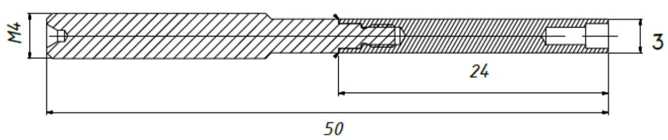


Fig. 2. Assembly of the FeCrAl core (right part). The left part is made in AISI 316L stainless steel.

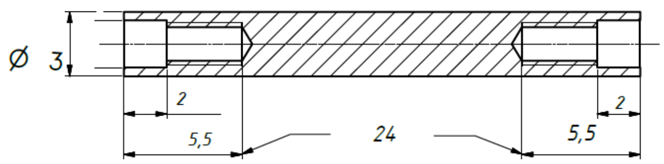


Fig. 3. Drawing of the FeCrAl core.

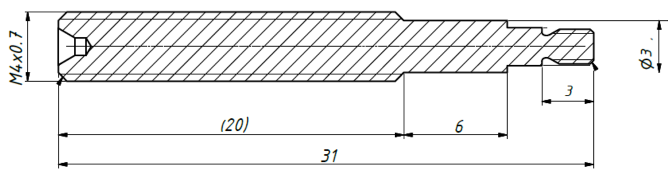


Fig. 4. Drawing of the core suspension part (AISI 316L).

Because no housing is needed, the magnetic core material can now have a diameter which is as large as the outer diameter of the non-magnet housing for the the SiFe core. In this prototype, the diameter was however slightly less; 3 mm instead of 3.3 mm. This larger diameter of the magnetic core will definitely increase the sensitivity of the LVDT. On the other hand, the magnetic permeability of FeCrAl is likely lower than that of SiFe.

## III. CALCULATIONS

Calculations of the sensitivity of the LVDT with the new core were made with the finite element software package QuickField.

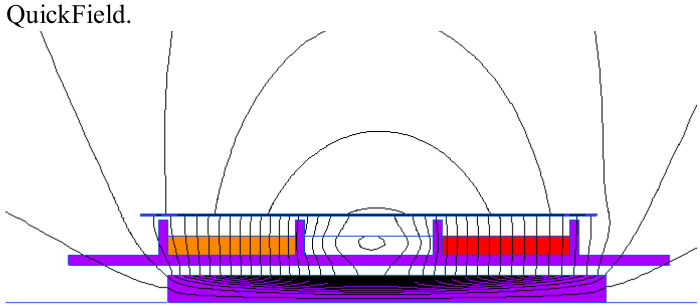

Fig. 5. Result of finite element calculations (QuickField) for the FeCrAl core, showing field lines.

The magnetic permeability of FeCrAl is not known, but it is likely lower than that of SiFe. The measurements (see further) show a total increase in sensitivity of 26 %. If the magnetic permeability of FeCrAl and SiFe (assumed relative permeability of 400) would have been the same, the finite element calculations (by QuickField) predict an increase in sensitivity of 43 %. In order to arrive at the experimentally observed improvement of 26 % (see later), the relative magnetic permeability of FeCrAl should be about 220 (as based on the calculations), thus about a factor 2 lower than that of SiFe. For the simulations, the core was displaced by 1 mm, the driving frequency was 1000 Hz and the driving current amplitude was 50 mA. The number of turns in each coil was 450. When changing the temperature of the FeCrAl core, the calculations showed only a very small increase in LVDT sensitivity with temperature. From 20 °C to 320 °C, the calculations show that the LVDT sensitivity was found to increase by only 0.2 %. For the same core geometry, the change in sensitivity for a SiFe core would be 13 %. In these calculations, the magnetic permeability was assumed to be independent of temperature. The measurements (see next section) indicate however that the latter effect is dominant.

## IV. MEASUREMENTS

In order to verify the performance of the new FeCrAl core relative to the standard Halden LVDT core, a Halden LVDT type 5 was used, while using respectively a standard Halden core (based on SiFe inside a housing) and a FeCrAl core.

### *A. Measurements at room temperature*

The LVDT and core were mounted in a room temperature calibration set-up which was designed for this purpose. Instead of using the standard Halden LVDT conditioning unit, a newly developed electronic unit was used (based on digital technology instead of the analog technology used in Halden). This new unit uses a coil driving current of 50 mA at an excitation frequency of 1000 Hz (whereas the Halden units work at 400 Hz). This higher frequency increases the sensitivity of the LVDT by a factor 1000/400 = 2.5. Here we will focus only on the relative sensitivities and the signal linearity.
Both the ac output of the secondary coils (measured by a Fluke 87V True RMS multimeter) and the DC output after demodulation (measured by a Fluke 787 process meter) were measured simultaneously for different positions of the magnetic core.

Fig. 6. Electronic units and calibration unit (on top) with mounted LVDT.

As shown in Fig. 7 to Fig. 10, the LVDT works very well with the new, simplified FeCrAl core. The sensitivity is even higher by 26 % as compared to the Halden core (see Fig. 9 and Fig.10). For both cores, one observes a slight deviation from linearity at the zero crossing. The deviation from linearity is slightly lower for the FeCrAl core.

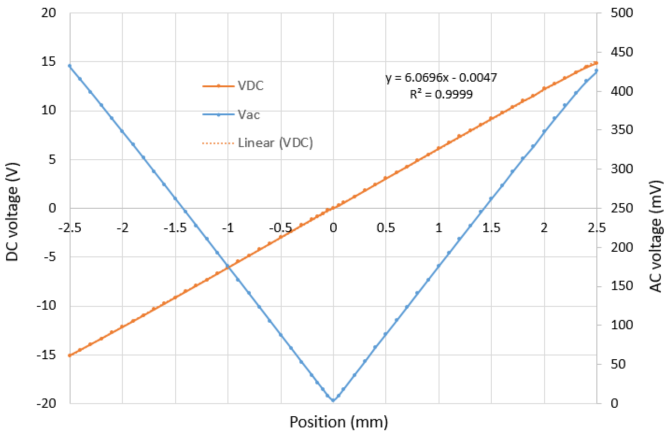


Fig. 7. Response of the LVDT with FeCrAl core.

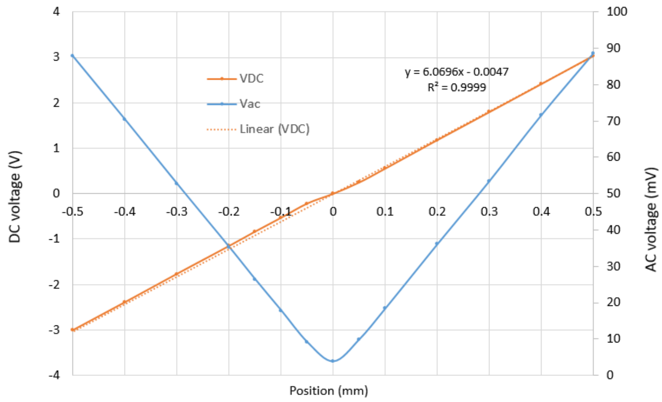


Fig. 8. Response of the LVDT with FeCrAl core showing a slight deviation from linearity of the DC signal at the zero crossing.

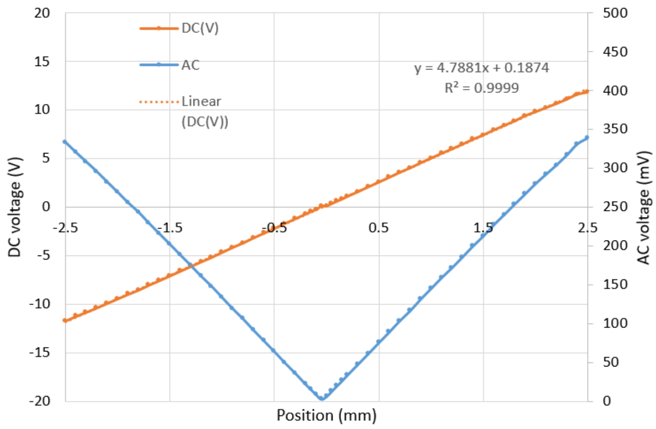


Fig. 9. Response of the LVDT with the Halden (SiFe) core.

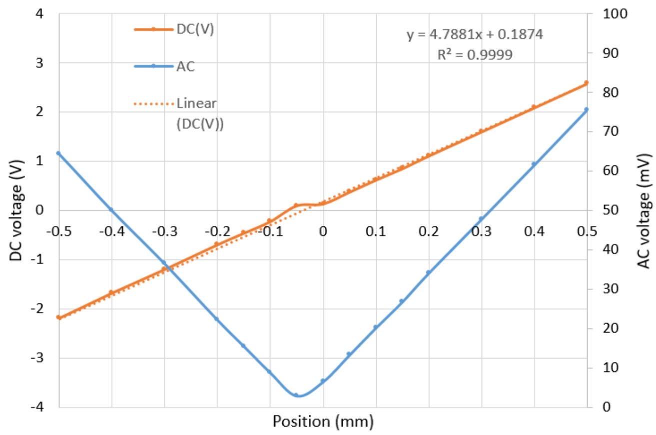


Fig. 10. Response of the LVDT with Halden core (SiFe) showing a slight deviation from linearity of the DC signal at the zero crossing.

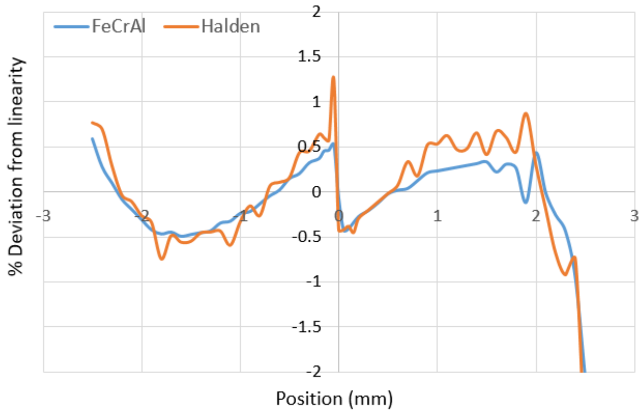


Fig. 11. Comparison of deviation from linearity between FeCrAl core and Halden core.

Fig. 12. High temperature LVDT calibration system.

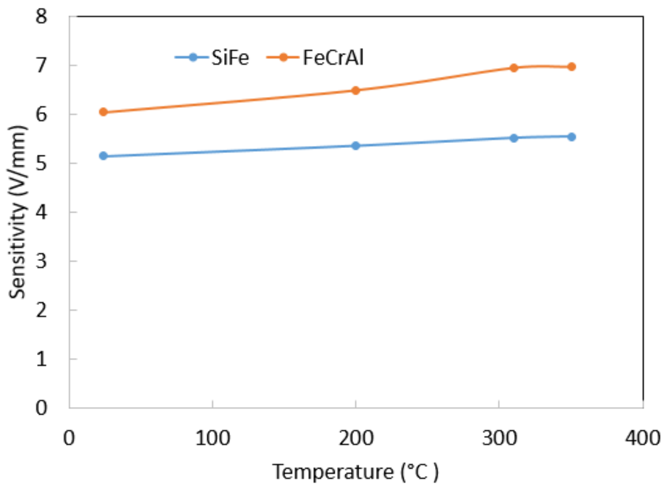


Fig. 13. Comparison of the LVDT sensitivity with SiFe and FeCrAl core.

*B. Measurements at high temperature*

A newly developed system for calibrating LVDTs at high temperature was used next (see Fig. 12). For the standard Halden LVDT and standard core (type 5), the sensitivity was measured with the newly developed conditioning unit, using a driving frequency of 1000 Hz. The sensitivity was found to increase from room temperature to 260 °C by 6.7 %. At a driving frequency of 400 Hz, the corresponding increase was 1.3 %. Thus the temperature dependence at 1000 Hz is a factor 5.15 higher than at 400 Hz. This factor is of the order of the ratio of the square of the frequency (6.25) and is in line with the fact that eddy current losses scale as the square of the frequency. The temperature dependence of the sensitivities at 400 Hz and 1000 Hz were found to be in good agreement with the calculated sensitivities (using QuickField), namely 1.3 % (400 Hz) and 6.07 % (1000 Hz), while assuming a constant magnetic permeability. Next, the LVDT sensitivities are compared with the SiFe and FeCrAl cores at different temperatures (see Fig. 13). The relative increase of the sensitivities for the two cores, relative to the sensitivities at room temperature are compared in Fig. 14.

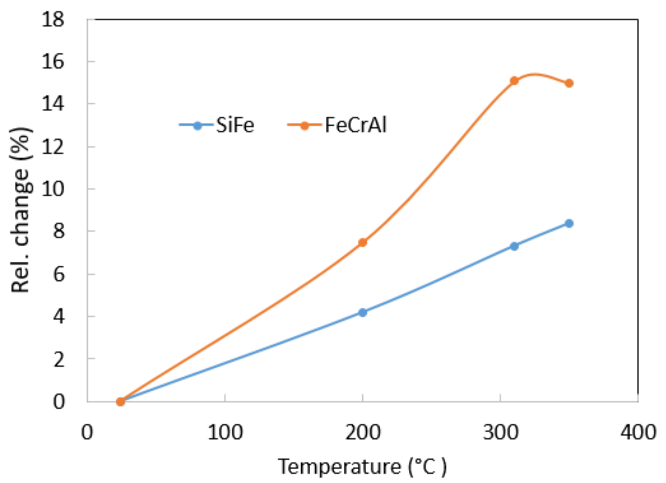


Fig. 14. Relative increase of sensitivity with temperature for the SiFe and FeCrAl cores.

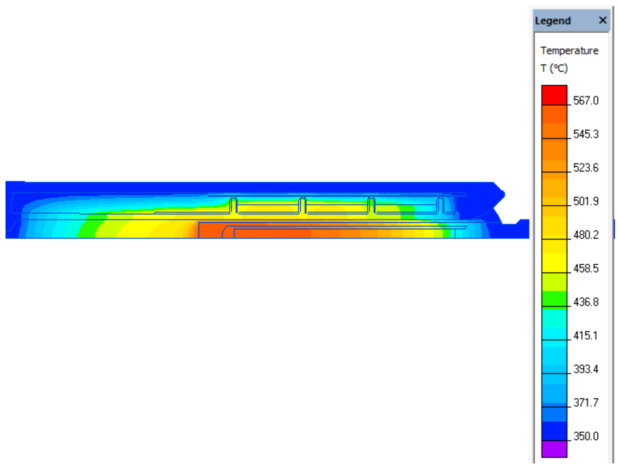


Fig. 15. Temperature distribution in an LVDT with standard core at a (stagnant) water temperature of 350 °C and a gamma heating of 5 W/g.

The higher dependence on temperature for the FeCrAl core cannot be explained by a change in eddy current losses but has to be due to a significant increase of the magnetic permeability of FeCrAl with temperature. According to the finite element calculations, the relative magnetic permeability should change from 220 at room temperature to 340 at 300 °C, thus corresponding to an increase of 54 %. If one would use the 5-wire electronic set-up, the relative increase of sensitivity from room temperature to 300 °C would be reduced from 15 % to 5 % (based on the finite element calculations).

## V. OPERATION AT HIGH GAMMA HEATING

The Halden type LVDT was designed to operate in the core of a reactor with flowing water at a maximum temperature of 350 °C (PWR conditions). The design is such that there is still some gap around the magnetic core for water to flow and there is an entrance and exit hole for this water at opposite sides of the magnetic core. In some special cases, a combination of high gamma heating and low water flow velocity can lead to overheating of the LVDT. An example of zero flow and a gamma heating of 5 W/g is shown in Fig. 15.
In this case, the water is converted to steam in the thin gap between magnetic core and the LVDT bore, resulting in a strongly reduced thermal conductivity in this region.

In this case, the temperature of the coils reaches 476 °C and the magnetic core reaches 566 °C. The Curie temperature of the SiFe core is around 700 °C, so the temperature of the core is still below it. However, the temperature of the coil is at the limit for the ceramic insulated nickel clad copper wire (used in almost all the experimental rigs in the Halden reactor). In the newer design, the wire is made of a ceramic insulated silver palladium alloy which allows continuous operation up to 500 °C. Nevertheless, such high temperatures are undesirable and the internal sealing of the mineral insulated wire can also be damaged at this temperature.
Another aspect to consider is that the temperature of the core is not uniform over its length. This is because the He-filled encapsulated core effectively behaves as a gamma thermometer. Even with sufficient flow, there is (for this case), a temperature difference between the tip and the base of the core of about 50 °C. This in turn will lead to a small variation of the magnetic permeability which will induce an imbalance of the signals generated in the two secondary coils, thus effectively mimicking a small displacement of the core.
Finally, at a gamma heating of 20 W/g (expected gamma heating for the JHR [3]), the finite element calculations show that the core temperature would reach 760 °C (above Curie temperature) in the case of water flow around the core and the LVDT would thus not function.
For the FeCrAl core, this effect can be avoided entirely since the core is not thermally insulated by a gas gap.

A further improvement could be obtained by making the core hollow. One could use a tube (3 mm outer diameter and 2 mm inner diameter), such that also water could flow through (and around) the core. This will allow a higher flow of water around the core resulting in a better internal cooling. This, in combination with a lower heated mass (as compared to a solid core) will allow operation at higher gamma heating. Detailed thermal and fluid calculations would be required to determine the actual temperature distribution for a particular situation.

## VI. Effect of irradiation

In the case of the Halden LVDT, the sensitivity drops by about 3 % during the first days of irradiation. This drop in sensitivity is thought to be due to the effect of fast neutrons on the magnetic permeability of the magnetic core. For an LVDT with a FeCrAl core, the effect of neutron irradiation has never been studied. The 3 % decrease for the SiFe core was observed using the 4-wire LVDT conditioning unit at a driving frequency of 400 Hz. With a 5-wire conditioning unit, the drop in sensitivity would be only 0.9 %, as based on the finite element simulations. Even if some drop in sensitivity upon irradiation would be observed for the FeCrAl core, the impact of it could likewise be made much smaller by operating the LVDT in 5-wire mode.

## VII. Conclusions

In the standard Halden LVDT, an encapsulated SiFe magnetic core is used, leading to excellent performance in terms of linearity and temperature sensitivity. Making the magnetic core of unprotected FeCrAl however, allows 1) to fabricate the core in a much simpler and cheaper way, 2) to increase slightly the linearity of the LVDT, 3) to use the LVDT at higher gamma heating up to 20 W/g (expected for the JHR).
The sensitivity of the LVDT with FeCrAl core increased from room temperature to 300 °C by 54 %, due to a significant increase of the magnetic permeability with temperature. Whatever the degree of sensitivity on temperature, it is shown that this can be reduced significantly by operating the LVDT in 5-wire mode. Finally, the LVDTs are always calibrated using a high temperature calibration set-up so that the sensitivity is determined in function of temperature.
Further, it is shown that changes in sensitivity due to neutron irradiation (during the first days of irradiation in a research reactor) can also be reduced significantly by operating the LVDT in 5-wire mode.

## ACKNOWLEDGEMENT

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