FLIBE ASSESSMENTS

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ABSTRACT

An assessment of the issues on using flibe for fusion applications has been made. It is concluded that sufficient tritium breeding can be achieved for a flibe blanket, especially if a few cm of Be is include in the blanket design. A key issue is the control of the transmutation products such as TF and F_2. A REDOX (Reducing-Oxidation) reaction has to be demonstrated which is compatible to the blanket design. Also, MHD may have strong impact on heat transfer if the flow is perpendicular to the magnetic field. The issues associated with the REDOX reaction and the MHD issues have to be resolved by both experimental program and numerical solutions.

I. INTRODUCTION

Flibe is a molten salt of LiF and BeF_2. It is one of the possible coolant/breeding materials for fusion applications. It has very low activation, low tritium solubility, low chemical reactivity, and low electrical conductivity, which lead to low MHD problems. Both APEX (Advanced Power Extraction)(1) and ALPS (Advanced Limiter-divertor Plasma-facing Systems)(2) designs are considering the use of flibe to form the free flowing blanket and divertor, respectively. A key reason to use flibe for APEX is that it attenuates neutron efficiently. A 30 cm of flibe can protect the structural material behind it to the life of the reactor. Thus, the regular first wall/blanket replacement will not be necessary during the plant life. Also, flibe has been used for other designs (3,4).

To assess the issues associated with using flibe in a fusion system, a flibe assessment task was formed. The major conclusions from this assessment group are:

1. The tritium breeding potential of flibe is marginal for a conventional blanket.. However, with a few cm of additional Be, tritium breeding will be sufficient.

2. With proper impurity control, flibe is compatible with most of the structural materials. The material compatibility issues are caused by impurities, and by transmutation products, such as TF.

3. REDOX (reducing-oxidation) reactions have been used in Molten Salt Breeder Experiments for impurity control. However, if Be is required for tritium breeding purpose, the REDOX agents will be reduced by Be. For those systems, REDOX reaction will not work.

4. Tritium permeation, caused by the low tritium solubility in flibe, will be a major concern.

5. MHD probably will not have significant impact on pressure drop. However, MHD may have major impact on heat transfer. This problem maybe very serious if the velocity is perpendicular to the magnetic field.

This assessment report defined the technical issues on flibe.

II. TRITIUM BREEDING

The tritium breeding potential of flibe has been a major concern. Earlier assessments concluded that a flibe blanket could not breed (5). This was a key reason that flibe was rated very low by the BCSS (Blanket Comparison and Selection Study) (6). However, recent calculation concluded that the 1-D breeding ratio for a conventional flibe blanket is about 1.2. With the addition of Be, higher breeding ratio can be achieved.

Figure 1 shows the tritium-breeding ratio of a flibe blanket as a function of the structural material fraction. With 5% V-alloy as the structure the tritium-breeding ratio is 1.16. This breeding ratio is marginal for a conventional blanket for a Tokamak configuration. However, it is sufficient for a HYLIFE type design (3), which has a large blanket coverage and very low structural fraction.

Tritium breeding can be improved by the addition of Be in the blanket. Figure 2 shows the tritium breeding for a flibe blanket with a Be zone. With a 10 cm Be zone, with 60% Be, the local tritium breeding ratio reaches 1.56. This breeding ratio is high enough to offset any uncertainties from 3-D effects, geometry effects, and cross-section data.

The composition of the flibe has only minor impact on tritium breeding. Also, only modest enhancement in tritium breeding results from lithium enriching in the flibe/V blanket.

III. MATERIAL COMPATI BILITY

The first step for the corrosion process is for the material to be dissolved in the coolant. Most metallic elements have very low solubility in the flibe. The only way that any metallic elements can be dissolved in the flibe is for that element to be oxidized first to metallic fluoride. Metallic fluoride, being a salt, has much higher solubility in the flibe. Therefore, the thermodynamics of formation of metallic fluoride provide a good indication of the compatibility between the structural materials and flibe.

Flibe is the molten salt of LiF and BeF_2. Both LiF and BeF_2 are very stable, and will not react with structural materials to form metallic fluoride. Therefore, pure flibe is very stable with structural materials and is compatible with large set of materials to high temperature. The materials compatible with pure flibe including Fe-based alloys, Ni-based alloys, graphite, SiC and most of the refractory metals.

However, impurities in the flibe can be rather unstable. If there are impurities in the flibe, the impurities can react with the structural materials to form metallic fluoride. This metallic fluoride will dissolved in the flibe and causing material compatibility issues. One of the impurities is tritium fluoride, with tritium produced in the blanket from the transmutation of lithium in the flibe. TF has low free energy of formation and is chemically active. One of the key issue on the flibe is t develop method to control TF activities, which will be discussed later in this paper.

The compatibility between as received flibe (with impurities) and 316 SS at 650°C is shown on Figure 3. (7). The corrosion rate by flibe on 316SS is rather high. However, after the flibe was treated by Be, during which all the impurities were reduced by Be to form BeF_2, the corrosion process almost stopped. This is the indication that the corrosion by flibe to the structural material is caused by impurities, not by the flibe itself.

IV. REDOX REACTION:

In a fusion reactor blanket, both Li and Be will be destroyed by transmutation reactions. With the destruction of Li and Be, fluorine will be freed to form either free fluorine or tritium fluoride. Both free fluorine and tritium fluoride are very reactive, and can react with the structural materials to form metallic fluoride. It is important to control the activities of TF and F_2 to an acceptable level.

The Molten Salt Breeder Program developed a REDOX (Reducing-oxidation) process to control the TF and F_2 activities by carefully control the TF/T_2 ratio (8). The REDOX reaction in the MSRX is based on the chemical reactions of

$$UF_3 + F \rightarrow UF_4,$$

and

$$2UF_3 + 2TF \rightarrow 2UF_4 + T_2$$

In a fusion reactor blanket, we do not have UF_3. Therefore, we have to develop a REDOX process. A possible REDOX process is based on the following chemical reaction (5),

$$CeF_3 + F \rightarrow CeF_4$$

No work has been performed to assess the possibility of using his chemical reaction to control either TF or F_2 activities.

As stated above, we may need addition Be in the blanket for neutron multiplication. BeF_2 is one of the most stable compounds, and will react with any REDOX agent to form BeF_2 and release the metallic element. Therefore, if we need Be in the blanket, no REDOX agent can survive. The only possible way to control the TF and F_2 activities is by the following reactions:

$$Be + 2F \rightarrow BeF_2,$$

and

$$Be + 2\,TF \rightarrow BeF_2 + T_2$$

There is no question that those two reactions will go forward from thermodynamics considerations. However, there is no assurance that whether those two reactions will go forward kinetically. To demonstrate that the TF and F_2 activities can be controlled is the most important issue for flibe research.

V. TRITIUM CONTROL:

The solubility of tritium in flibe is very low. Therefore, an efficient tritium recovery system needs to be developed. Even with an efficient tritium recovery system, the tritium partial pressure over the flibe will still be very high. With a high temperature system for efficient power conversion, tritium control will be a key issue. The most severe issue on tritium control is in the primary heat exchanger, where the surface area is large, and the tube wall is thin. Tritium can be controlled by either efficient recovery, or by reduce the permeation rate.

A tritium recovery process called vacuum disengager was proposed in the HYLIFE design (3). The key concept is to recover tritium to a sufficient low level efficiency that the tritium flow rate to the primary heat exchanger is less than allowable permeation rate. Since the tritium production rate is about 500 g/FPD (Full Power Day), while the allowable tritium permeation rate is 100 Ci/FPD, the tritium recovery system has to be 99.999% efficient. The design calls for two gas-liquid contactor operating in series, each with 99.7% efficiency. The efficiency of each unit can be calculated by mass diffusion and evaporation rate from the flibe surface. However, no experimental work is available to assess the feasibility of this process.

A second method is to reduce the tritium permeation. A tritium-diffusing barrier is a possible way to reduce tritium permeation. However, the reduction factor of a tritium-diffusing barrier is only about a factor of 100, far less than that required for tritium control. The required reduction factor is 10^7. Another possible method is to use a structural material with low tritium permeability. One such material is SiC. If SiC is used for the structural material for the heat exchanger, the permeation rate is essentially zero.

Tritium control is another key technical issue needs to be resolved for flibe research. Since both the tritium solubility, and TF/F_2 control, strongly depends on the chemical state of the flibe, those two problems have to be resolved together.

VI. MHD ISSUES:

Flibe is a molten slat and has a low electrical conductivity. It was assumed that there was no MHD issue for using flibe in fusion applications. However, this assessment uncovered possible MHD effects on both pressure drop and heat transfer. Most experimental results were done for liquid metals, with parameters similar to using flibe in fusion applications. Since heat transfer and fluid mechanics depends only on dimensionless parameters, we can use results from experiments to predict what will happen for the flibe.

Figure 4 shows the effect of MHD on pressure drop (9). For typical blanket operation, the Re number is about 100,000, while the Ha number is about 100. Within this range the effect of MHD on pressure drop is minor, and can be neglected at this time. Table 1 summarizes the parameters for a typical flibe blanket.

Table 1. Typical Blanket Parameters

Velocity, V	10 m/s
Tube diameter, d	0.1m
Viscosity	0.015 Kg/s-m
Density	2000 kg/m3
Re Number	$1.33 \times 10^{5)}$
Magnetic Field, B	16 Tesla
Characteristics dimension, a	0.05 m
Electrical conductivity	155 ohm/m
Ha number, Ha	80

Figure 5 (10) shows the effect of MHD on heat transfer with magnetic field perpendicular to the velocity. The following equations are suggested to predict Nu number, for flow perpendicular and parallel to the magnetic field, respectively.

For a flow in a transverse magnetic field, the heat transfer can be represented by,

$$Nu = 10.0 + 0.025\left(\frac{Pe}{1 + (236Ha^2 / \mathrm{Re})}\right)^{0.8}$$

For a flow in a parallel magnetic field, the correlation becomes,

$$Nu = 9.0 + \left(\frac{0.006Pe}{1 + (14.8Ha^2 / \mathrm{Re}}\right)$$

in which

Re is the Reynolds number (= DVρ/μ)
Nu is the Nusselt number (=hD/k)
Pe is the Peclet number (=DVρCp/k)
Ha is the Hartmann number (=BD (ρ/μ)⁻)
D is the dimension of the coolant channel
v is the velocity
ρ is the density
μ is the viscosity
h is the heat transfer coefficient
k is the thermal conductivity
Cp is the heat capacity
B is the magnetic field
σ is the electric conductivity

The first terms of those equations are the contribution from conduction, also shown on Figure 4. The second terms of those equations are the contribution from the convection, and the term of Ha^2/Re is the reduction of the convection heat transfer due to the MHD effects. Since those equations and Figure 4 are obtained for liquid metal systems, they cannot used directly to predict the effects of MHD on heat transfer, but can certainly give us some indication. With this results, it can be predicted that MHD may have dominate effects on heat transfer when magnetic field is perpendicular to the velocity, while there will be a minor effect on heat transfer if the magnetic field is parallel to the velocity.

Experimental program will be required to assess the effects on MHD on heat transfer. If the impact on heat transfer is severe when velocity is perpendicular to the magnetic field, the design will align the velocity to be parallel to the field along the first wall.

CONCLUSIONS:

Some key issues for the flibe blanket have been identified. The key issues are the chemistry and tritium control, and the effects of MHD on heat transfer. Pure flibe is compatible to many structural materials. However, transmutation product of TF and F_2 will cause compatibility issues. A chemical process has to be developed to control the TF and F_2 activities. With this established chemical state, a process to recovery tritium and limiting tritium permeation rate to an acceptable level has to be demonstrated. One of the possible process is using Be as the reducing agent to reduce both TF and F_2 into the BeF_2 form.

There maybe large MHD effects on heat transfer. In particular, this MHD effects can be severe if the magnetic field is perpendicular to the velocity. There is no experimental data to predict this MHD effects on a molten salt. The conclusion is based on liquid metal experiments with Re and Ha numbers similar to that for file in a fusion blanket. Both experimental results and theoretical modeling are required to predict the effect of MHD on heat transfer.

Neutronic calculation concluded that, if a few cm of Be is added in the blanket, tritium breeding will not be an issue. If there is no additional Be, tritium breeding is marginal for a conventional blanket, but will be sufficient for a free flowing blanket with high coverage and low structural fraction.

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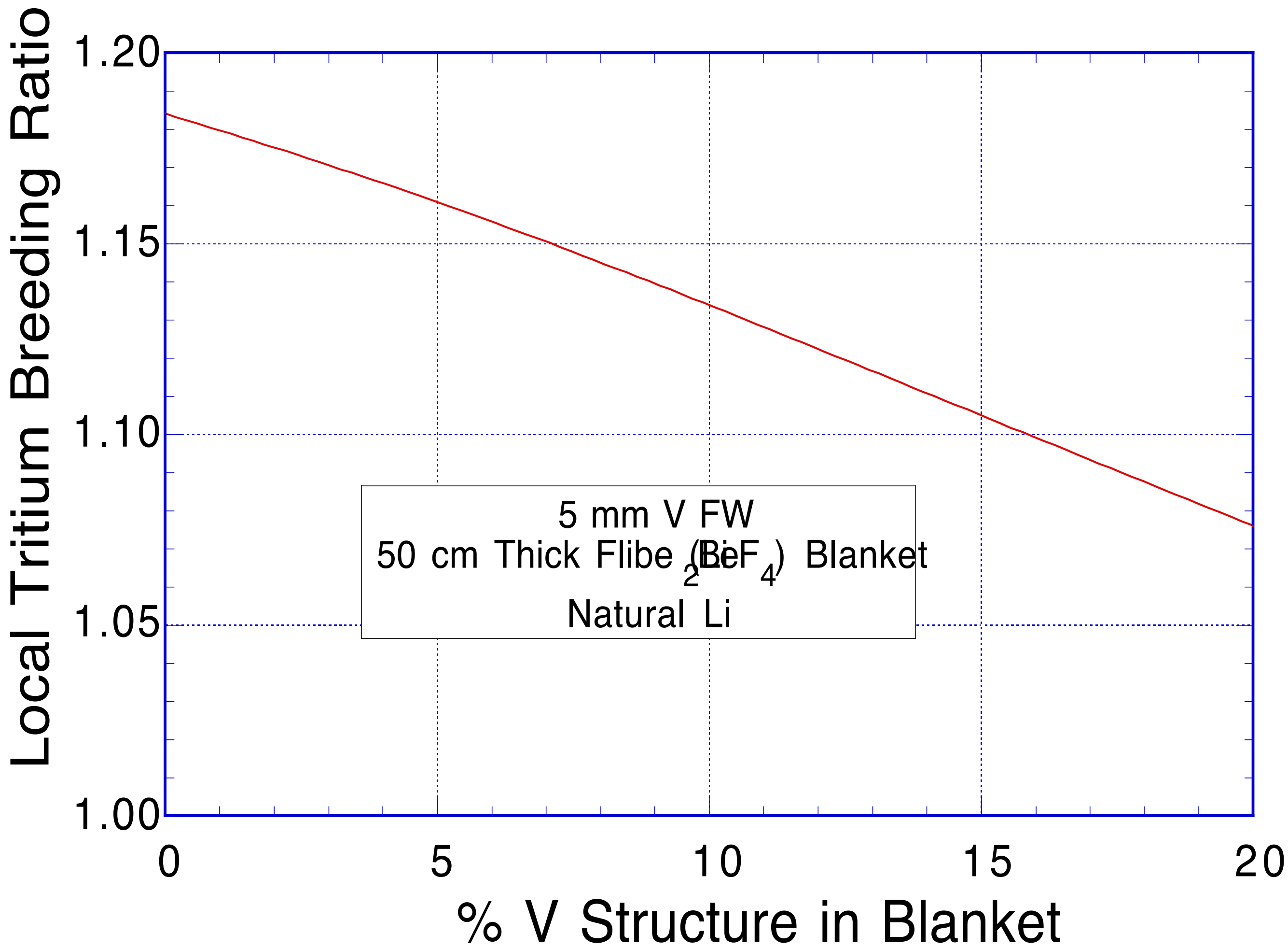

Figure 1. Tritium Breeding Ratio in a Flibe/V Blanket

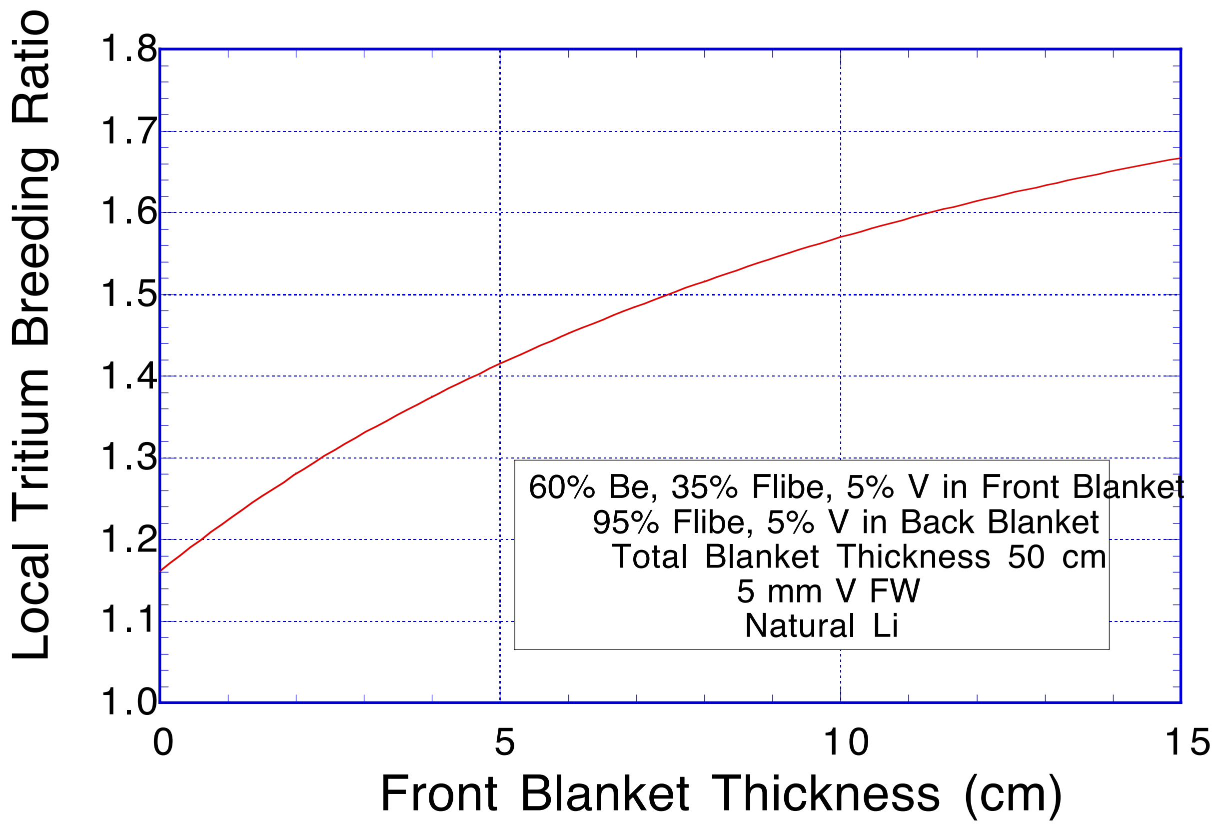

Figure 2. Impact of Be to Tritium Breeding Ratio in a Flibe/V Blanket.

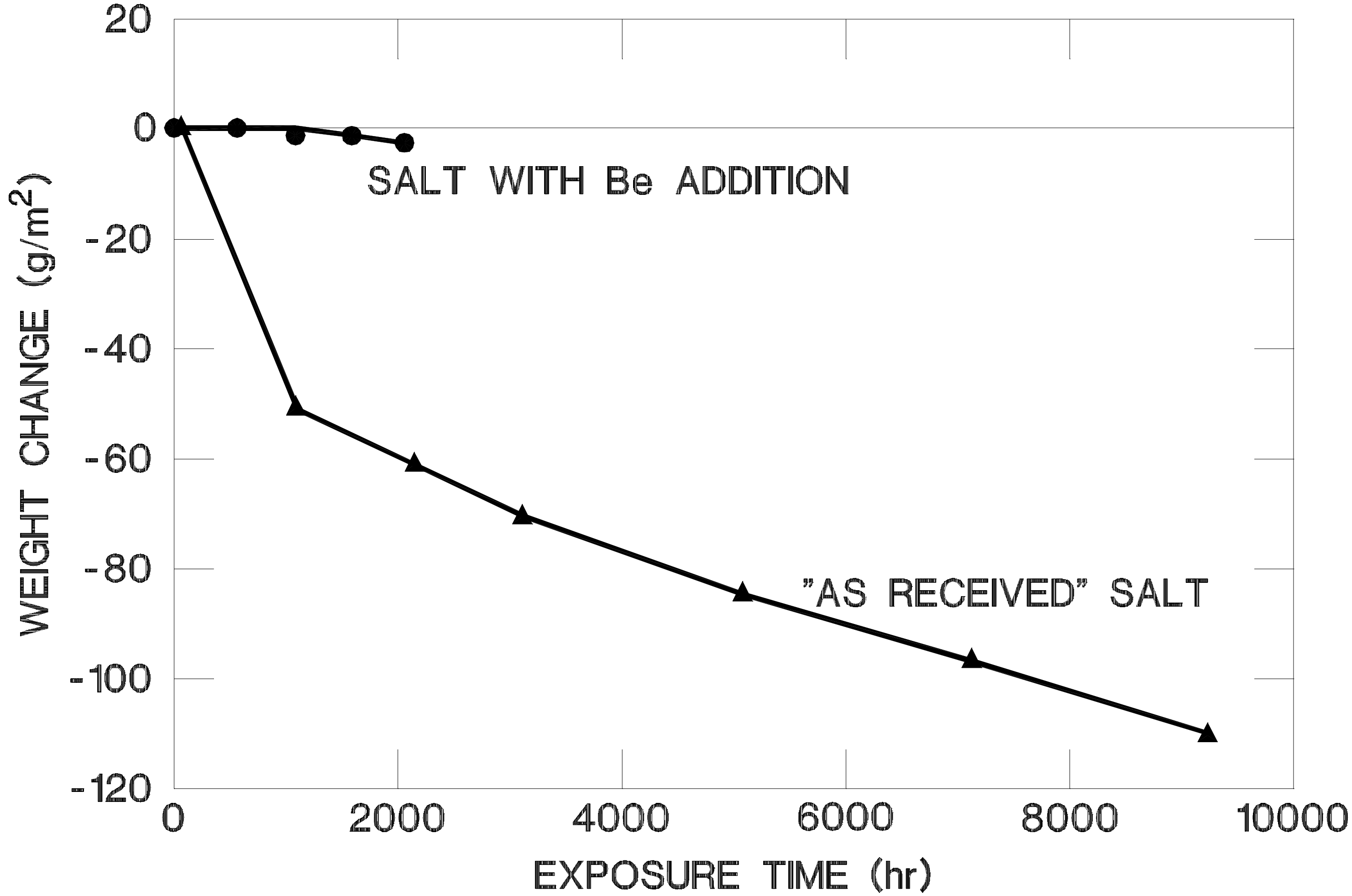

Fig. 3 Weight change versus exposure time for type 316 stainless steel in $LiF-BeF_2$ salt at the maximum loop temperature of 650 °C.

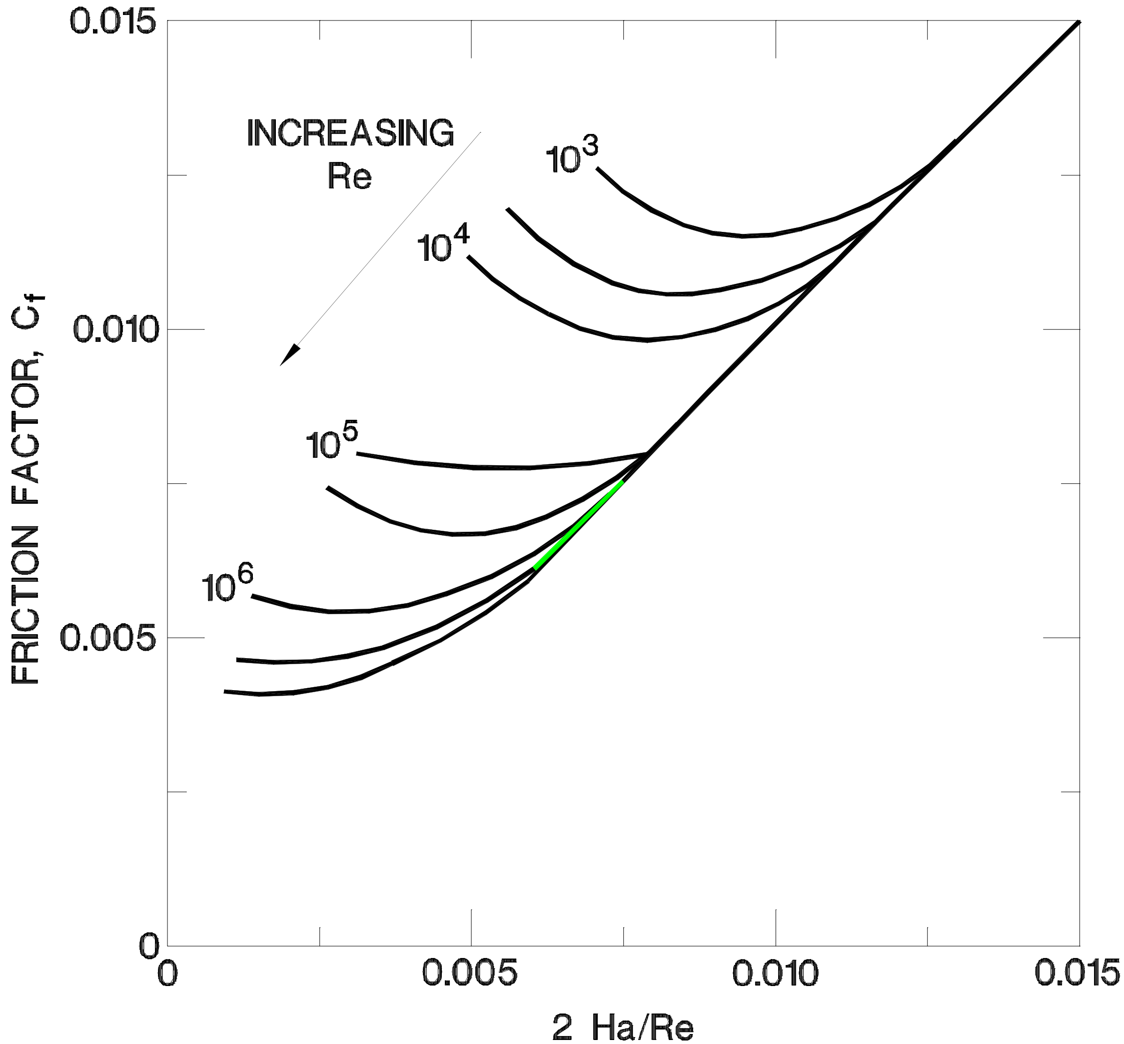

Fig. 4 Effect of MHD on pressure drop.

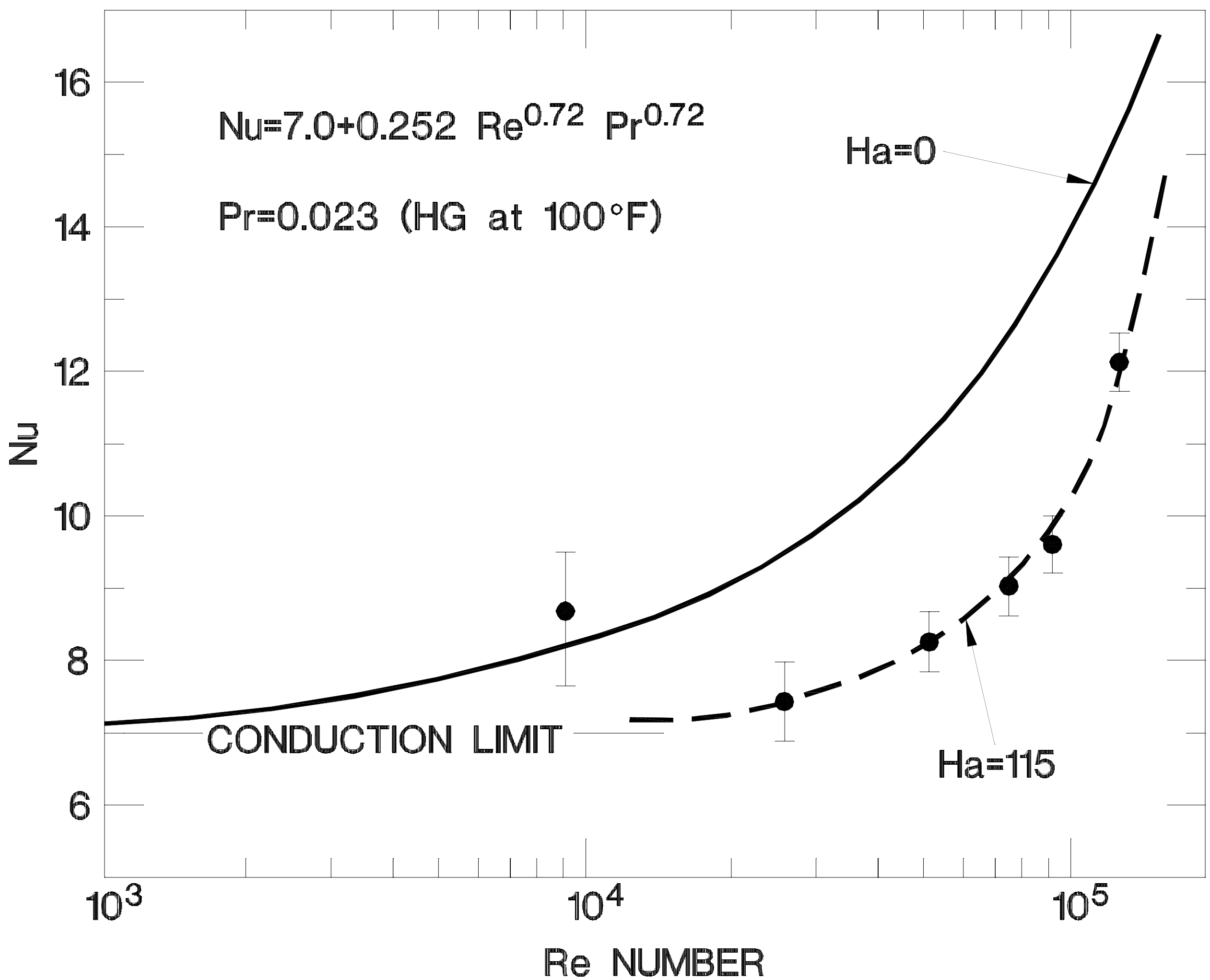

Fig. 5 Effect of MHD on heat transfer.