ACTINIDE BREEDING AND BURNING IN METALLIC AND OXIDE FUELED ALMR CORES

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ABSTRACT

The reference design of the ALMR is a 471 MWt modular breeder reactor. The reference fuel for this core is a metallic alloy of U, Pu, and Zr. In this study, the design of an alternative oxide fueled ALMR is presented and compared with the reference design. Fuel utilization in the oxide fueled core is not as good as in the reference ALMR, and a higher fissile inventory is therefore required.

Also, an oxide fueled burner is developed based on the alternative oxide fueled design and compared with a metallic fueled burner based on the reference design. This study shows that when an oxide fueled burner is optimized within the same geometrical configuration and within the same limits and constraints as an optimal designed metallic fueled burner, the oxide fueled burner might perform as well as or even better than the metallic fueled burner.

INTRODUCTION

The modular reactor concept, PRISM (Power Reactor, Innovative, Small Module), originated by General Electric, in conjunction with the Integral Fast Reactor metal fuel pyroprocess being developed by Argonne National Laboratory (ANL), is the reference reactor of the US DoE Advanced Liquid Metal Reactor (ALMR) programme. The reference design of the ALMR is a 471 MWt modular breeder reactor [1]. The reference fuel for this c-ore is a metallic alloy of U, Pu, and Zr. However, in international markets the oxide fuel cycle system has a well established infrastructure. The ALMR should be deployable in these markets as well as in the U.S. In this study, the design of an alternat ive oxide fueled A LMR is present ed and compared with the metallic fueled reference ALMR design. The alt ernative oxide fueled AL MR is designed to have the same operational characteristics and to fit in the same geometrical configurate ion.

Also, an oxide fueled burner is developed, which burns actinides at the highest possible rate without violating limits and constraints on the reactor design, and which will be compared with the metallic fueled burner design presented in reference 1, which was also designed to be an optimal burner. These two burner designs are compared on their t ransmutation effectiveness.

DESIGN PHILOSOPHY

In carrying out the core design optimization, special attention has to be focussed on the following important performance parameters:

1. The burnup reactivity swing should be kept low for bet ter performance and safety of the core.
2. The peak fuel burnup should be limited to about 150 MWd/kg to limit the cladding strain from the fission gas buildup in the upper plenum region and to assure proper fuel performance and fuel pin integrity.

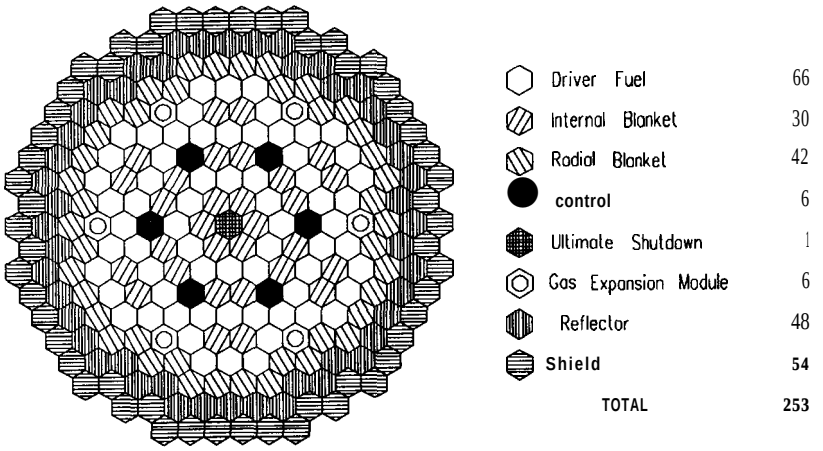

Figure 1: Core layout of the metallic- fueled ALMR design

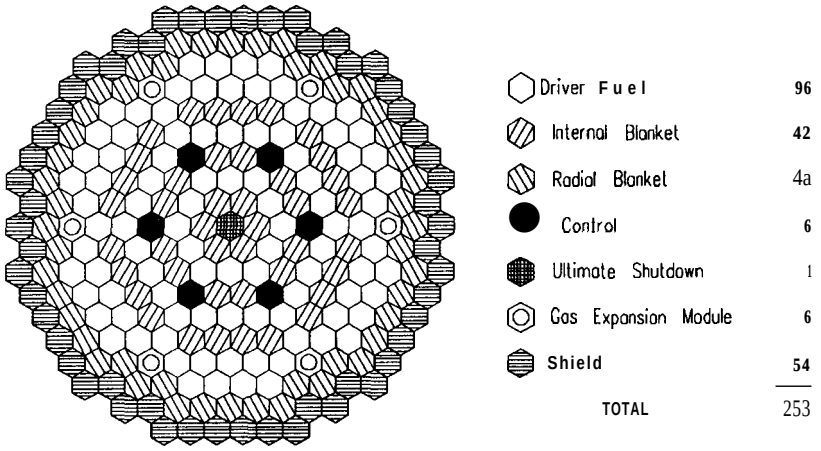

Figure 2: Core layout of the oxide fueled ALMR design

3. The peak fast neutron fluence should be limited to about $3.6 \cdot 10^{23}$ n/cm^2. This limit is based on constraints imposed by the use of ferritic steel HT9 as the core structural material. which might swell appreciably above this fluence.

4. The core should achieve at least break-even, i.e. a breeding ratio of approximately 1.05.

5. The radial power distribution should be relatively flat to minimize peak linear heating, peak burnup, and peak fast neutron fluence.

6. The transuranic (TRU) enrichment in the oxide fuel should be less than about 33 w/o, to ensure proper fuel fabrication. Above this enrichment, hydrogen-fluoride has to be used in fuel processing, which will lead to a strong increase of the fuel fabrication costs [2].

Using the design parameters listed above. the core layout for the alternative oxide fueled ALMR core with optimal characteristics was designed.

For the oxide burner design, the same performance parameters should be attained. except for the breeding ratio. Because the breeding ratio will

be less than one, the burnup reactivity swing will be larger. The burnup reactivity swing should be less than 12$ to ensure proper reactivity control.

ALTERNATIVE OXIDE FUELED ALMR

The alternative oxide fueled core for ALMR is a heterogeneous, mixed oxide fuel design with 253 assemblies: 96 fuel assemblies, 42 internal blanket assemblies, 48 radial blanket assemblies, 54 reflector/shield assemblies, 6 control assemblies, 6 gas expansion modules, and one ultimate shutdown assembly. The core layout for the metallic fueled and oxide fueled designs are shown in Figures 1 and 2.

The number of both fuel and blanket assemblies is much higher for the oxide fueled design than for the metallic fueled design, while the number of shielding assemblies is decreased for the oxide fueled design. Table 1 provides a summary of the core design parameters and core design characteristics of the oxide fueled core compa.reel to the metallic fueled core. With the results on the neutronics performance and the design characteristics presented in Table 1, the differences in performance between oxide fueled and metallic fueled ALMR cores will be discussed. A more extensive discussion is presented in reference 3.

For the oxide fueled design, the whole core layout had to be changed. At first, the same core design was used as for the metallic fueled core, but then the TRU enrichment was much higher than 33 w/o, which is approximately the practical limit set on the TRU enrichment [2]. This is caused by two principle differences between oxide and metallic fuel. First, the oxide fuel density is smaller than the metallic fuel density, leading to a higher required enrichment for the oxide fuel. Second, oxide fuel has a softer spectrum due to the slowing down of neutrons by the oxygen nuclides in the fuel. The median energy of the neutron flux spectrum is 152 keV for the oxide fueled core and 219 keV for the metallic fueled core. A softer spectrum affects the neutron economy in two ways:

- Poorer neutron utilization caused by a lower ratio of effective fission to capture cross sections, and a smaller U-238 effective fast fission cross section,

Table 1: Design parameters and characteristics for the reference metallic fueled ALMR core and for the alternative oxide fueled ALMR core

General Core Desire		
	Metal	Oxide
number of in-core batches	3	8
total number of batches	5	10
cycle time [months]	24	16.8
total in-core time [months]	72	134.4
DF height [cm]	141.4	152.4
DF+AB height [cm]	141.4	193.0
fuel assembly HM mass [kg]	92.0	120..5
TRU enrichment [wt %]	31.6	33.8
Fissile Pu Inventory BOEC [kg]	13s1	2170
volume fraction fuel [%]	35.8	44.1
number of DF assemblies	66	96
number of IB assemblies	30	42
number of RB assemblies	42	48
assembly flow area [cm^2]	57.6	42.8
pin diameter [cm]	0.721	0.897
General Core Performance		
	Metal	Oxide
Breeding Rat io	**1.08**	1.09
CSDT [years]	1312	9536
Burnup Reactivity Swing [$]	-3.00	-1.95
Average DF Burnup [MWd/kg]	100.8	106.5
Peak DF Burnup [MWd/kg]	14s..5	157.8
Fissile Pu Gain [kg/y]	6.0.5	3..56
Peak Total Flux [$10^{15} cm^{-2}s^{-1}$]	3.21	1.93
Peak Fast Flux [$10^{15} cm^{-2}s^{-1}$]	2.14	1.12
Peak Fast Fluence [10^{23} en-2]	3.34	3.36
capture rate [% of SN]	51.5	57.2
fission rate [% of SN]	34.1	34.5
leakage [% of SN]	14.6	8.5
median energy DF [keV]	219	152

AB = Axial Blanket
BOEC = Beginning of Equilibrium Cycle
CSDT = Compound System Doubling Time
DF = Driver Fuel
HM = Heavy Metal
IB = Internal Blanket
RB = Radial Blanket
SN = Source Neutrons
TRU = Transuranics

- Lower leakage in the oxide fueled core due to

the higher effective total cross section.

The combined effect is a higher enrichment requirement for the oxide fueled core. This problem was addressed by decreasing the leakage of the oxide fueled core by increasing the number of fuel and blanket assemblies and by increasing the diameter of the fuel pins in the assemblies. Lower leakage increases the reactivity of the core design. The increased pin diameter results in a smaller assemby coolant flow area. This flow area could be lowered, because the total power production per assembly is lower due to the higher number of assemblies. The fuel volume fraction is 0.441 for the oxide fueled assembly design compared to 0.358 for the metallic fueled assembly design.

To achieve an economic feasible design, the burnup of the fuel assemblies has to be as high as possible. So, in the design process, the peak burnup of the core has to be as close as possible to the limit on burnup, which is approximately 1.50 MWd/kg, and the power peaking has to be as low as possible to achieve the highest average burnup and to get optimal thermal-hydraulic performance. The burnup rate of the assemblies decreased due to the decrease in power production per assembly. To reach the limit on burnup, the in-core residence time is increased, which could be done by increasing the cycle time or by increasing the number of batches. Because the burnup reactivity swing has to be low to reduce excess reactivity, only the number of batches is increased from 3 to 8. In fact, the cycle time is lowered from 24 months to 16.8 months to achieve a reasonable burnup reactivity swing.

One single enrichment. is used for the fuel assemblies. The fuel is mixed TRU-U oxide with a TRU enrichment of 33.8 w/o compared to 31.6 w/o TRU enrichment for the metallic fueled core. The TRU isotopic composition of the start-up fuel for both reactors is taken from the TRU composition of the U.S. Light Water Reactor (LWR) spent fuel. The uranium for the fuel assemblies and the fresh blare ket fuel is assumed to be depleted uranium.

The reactivity loss per refueling cycle due to fuel burnup is 1.95$ (674 pcm), which is much lower than 3$ for the metallic fueled core. This burnup reactivity swing affects the control system in two ways: 1) it is a major contributor to the positive reactivity in a control rod withdrawal accident, and 2) it reduces the available control rod scram worth at BOEC since the control rods need to be partially inserted into the core to suppress the excess reactivity to accommodate for the burnup reactivity loss.

The total fluxes represent the neutron population integrated over the entire neutron energy spectrum while the fast fluxes are defined for those neutrons with energies greater than 0.1 MeV, which is considered the lower bound for neutron irradiation damage to material. For the driver fuel, the peak total flux is 1.93 x 10^{15}cm^{-2} s^{-1} at BOEC. The peak fast flux is 1.12 x 10^{15}cm^{-2}s^{-1}. These fluxes are substantially lower than the values for the metallic fueled core due to the lower power density in the oxide core.

The peak fast fluences for the discharge fuel and blanket assemblies are 3.36 and 2.52 x 10^{23} n cm-z, respectively. These peak fluences are substantially lower than 3.6 x 10^{23} n cm^{-2}, which is considered to be the fluence limit for the structural material HT9 with regard to the irradiation induced swelling. For the oxide design, the peak fuel burnup limits the in-core residence time of the fuel assemblies and not the peak fast fluence. For the blanket, assemblies, it was not possible to increase the in-core residence time for the shuffling scheme considered, which achieved the lowest power peaking.

The fissile inventory is 2170 kg, or 4.61 kg/MWt, compared to 13S1 kg or 2.93 kg/MWt for the metallic fueled core. The fissile gain per cycle of the driver fuel and discharged blanket assemblies is 3.6 kg, compared to 6.1 kg for the metallic fueled core. The average breeding ratio measured in fissile plutonium mass of the oxide fueled core is 1.09 compared to 1.08 for the metallic fueled core. Another important measure of breeding capability is the compound system doubling time (CSDT), which is defined as follows :

$$CSDT = \frac{ln2 \cdot T_{cyc} \cdot (M_{in} + M_{ex})}{G - L_p - L_d}$$

where,

T_{cyc}=Cycle length (refueling interval).
M_{in}=In-core fissile Pu inventory at BOC,
M_{ex}=External cycle fissile Pu inventory for reload.
G=Fissile Pu gain per cycle.
L_p=Fuel cycle loss in fabrication and reprocessing, and
L_d=Pu-241 decay loss.

Based upon the above definition, with a loss fraction of 0.01, the CSDT is computed to be 9500 years, while the CSDT for the metallic fueled design is 1300 years. These very long doubling times reflect the inferior neutron economy of a small core such as the ALMR, which is especially true for the oxide fueled design. It should be noted that improvement in the breeding gain and doubling time, which may be of paramount importance in the future when accelerated LMR deployment is envisioned, could not be easily accomplished without enlarging the current core size for the oxide fueled core. The oxide fueled core fits in the same geometrical configuration, but the amount of shielding has been decreased in favor of more fuel assemblies. The lower total flux allows for less shielding, but detailed shielding analysis has to be done to determine whether the designed shielding is sufficient.

Although the safety characteristics of this oxide fueled core have not yet been determined, some qualitative comments can be made on the behaviour of this core compared to the metallic fueled core. The Doppler effect in the oxide fueled core will be higher due to the softer neutron spectrum. For the sodium void coefficient, it is difficult to make a qualitative statement about the difference between the oxide and the metallic fueled cores due to the influence of more fuel assemblies and a smaller duct-to-duct gap. Three generic beyond design basis accidents have been defined to be important for the safety analysis of the ALMR reactor: Loss Of primary Flow (LO F), Transient OverPower (TOP), and Loss of Heat Sink (1.011S) [4]. The oxide fueled core is expected to perform comparable to the metallic fueled core except for the LOF event, due to the higher heat capacity and the lower heat conductivity of the oxide fuel. Transient analysis will be performed to check these qualitative comments.

METALLIC AND OXIDE FUELED ALMR BURNERS

In this section, an oxide fueled burner design is presented and compared to a metallic fueled burner, which was already presented in reference 1. For the burner designs, all internal blanket, assemblies are changed into fuel assemblies to avoid breeding of new fissile material. Both burner cores use the assembly design of the metallic fueled reference core with a fuel volume fraction of 0.3.58. The burner cores are operated with two enrichment zones to reduce power peaking. The lower enrichment zone is situated in the center of the core and consists of 30 elements for the metallic fueled design and 84 elements for the oxide fueled design. The higher enrichment zone is situated around the lower enrichment zone and consists of 66 elements for the metallic fueled design and 54 for the oxide fueled design. For the oxide fueled design, the axial blankets are removed. The core height is lowered as much as possible to obtain a low conversion ratio, which is a parameter for the transmutation effectiveness. For the metallic fueled burner desigu, the core height, is 106.7 cm compared to 141.4 cm for the reference core. For the oxide fueled burner design, the core height is 95.3 cm compared to 152.4 cm for the alternative core.

In Table 2, a summary of the design characteristics is presented for the metallic fueled burner [1] and for the oxide fueled burner.

In the presented designs, the oxide fueled burner operates with six batches, whereas the metallic fueled burner operates with three batches. The cycle length for tile metallic fueled design is somewhat, longer than for the oxide fueled design. but the total in-core residence time is much longer for the oxide fueled design than for the metallic fueled design. In the design process, the in-core residence time of the fuel assemblies is maximized and is limited by the peak fast fluence. The in-core residence time for the oxide fueled design is allowed to be longer than for the metallic fueled design, because the peak fast flux is much lower for the oxide fueled design. The cycle length is maximized for economical reasons and is limited by the burnup reactivity swing (max. 12$). The burnup reactivity swing for the metallic fueled design is almost equal to the limit on this parameter [1], while for the oxide fueled design the burnup reactivity swing is somewhat lower than the limit.

The feed fuel enrichment is much higher for the oxide fueled design than for the metallic fueled desigu and therefore the TRU mass at BOEC is higher for the oxide fueled core due to the relat ive lower fission to capture cross section ratio for most actinides in the oxide fueled core. This is due to the fact that the spectrum of the oxide fueled core is softer than the spectrum of the metallic fueled core. Also, the average fuel burnup values arc much higher for the

Table 2: Design parameters and design characteristics for the metallic fueled ALMR burner core and forthe oxide fueled ALMR burner core

	Metal	Oxide
General Core Design		
number of in-core batches	3	6
total number of batches	5	8
cycle time [months]	15	12
total in-core time [months]	45	72
height [cm]	106.7	95.3
fuel assembly HM mass [kg]	73.5	46.2
General Core Per formance		
average conversion ratio	0.69	0.67
burnup reactivity swing [$]	-11.5	-10.5
average DF burnup [MWd/kg]	76.4	103.8
peak DF burnup [MWd/kg]	121.7	167.5
peak linear power [kW/ft]	10.8	13.0
peak fast fluence $[10^{23}cm^{-2}]$	3.63	3.51
peak fast flux $[10^{15}cm^{-2}s^{-1}]$	3.70	2.20
power peaking	1.715	1.5.52
high fuel enrichment [%TRU]	25.8	32.2
low fuel enrichment [%TRU]	21.3	26.6
TRU mass [kg]		
loaded per cycle	539.4	333.2
discharged per cycle	475.6	275.9
nett burned per cycle	63.8	57.3
inventory at BOEC	1550.3	1841.3

oxide fueled design than for the metallic fueled design due to the longer in-core residence time and the lower power peaking for the oxide fueled design. Less power peaking makes a higher average fluence value possible throughout the core. For both designs, the peak fuel burnup and the peak linear power values are below their limits.

ACTINIDE BURNING WITH THE METALLIC AND OXIDE FUELED BURNERS

In order to evaluate the performance of a system on actinide burning, the inventory reduction factor will be used. The concept of inventory reduction was introduced by Pigford [5,6], and is used to evaluate the reduction of nuclear waste for a system of LWRS and burners compared to a system of LWRS with the same power production operating in once-through mode. The inventory reduction factor I is defined by

$$I(t) = \frac{F/w,(t) + W_{lwr}(t)}{F_{sc}(t) + W_{sc}(t)} \quad (1)$$

Here, $F_{sc}(t)$ is the TRU inventory at time t of the reactors operating for the scenario considered, $W_{sc}(t)$ is the integrated amount of TRU waste at time t produced during operation of these reactors, $F_{lwr}(t)$ is the TRU inventory of the LWRS producing the same amount of energy as the reactors in the scenario considered, and $W_{lwr}(t)$ is the integrated amount of TRU waste produced by these LWRS including the initial amount of TRU waste. This concept is applied to the amount, of TRU mass, which is considered as an approximate measure of the toxic inventory of nuclear waste.

In reference 7, the methodology to calculate the reduction factor when a set of ALMR burners is operating in symbiosis with a set of LWRS is presented for a specific energy production scenario. The number of LWRS operating in the U.S. before ALMR burners go into operation is estimated to be 100 [8], they will have producedan amount of 900 tonne (MT) of TRU waste in about 30 years before ALMRs are started [5]. The fast decline energy scenario of reference 7 is used, which implies that ALMRs will be fueled at startup with the TRU mass available at the start of this energy scenario, and that parallel to the startup of ALMRs, some LWRS will be shutdown to keep the total power production constant. After a period of 50 years, during which the number of ALMRs will increase slightly and the number of LWRs will decrease correspondingly to assure constant power production, the remaining LWRS will be shutdown instantaneously and the power production will drop. The ALMRs will still be in operation to burn the fuel inventories of the LWRS and also of the ALMRs. This will take some hundreds of years, during which the number of ALMRs will decrease gradually because of burnup of the TRU inventory. Each time an ALMR is shutdown, the TRU inventory of that ALMR will be used as fuel for the remaiuing ALMRs, until only at least one ALMR is left, whose fuel inventory has to be disposed of.

The method presented in reference 7 is used to calculate the reduction factor for the energy scenario described in this section. The total fuel inventory at the beginning of equilibrium cycle (BOEC), the

discharged mass per year and the burned mass per year, all in terms of TRU mass per burner, are input. These quantities have been determined in the neutronics evaluation as described in this paper and are given in Table 3. The total fuel mass is defined as the out-core fuel mass added to the in-core fuel mass.

Table 3: Input parameters for LWRS, metallic fueled and oxide fueled ALMR burner cores for the calculation of the inventory reduction factor. All reactors are normalized to operate at 471 MWt

	Input Parameter	TRU Mass
LWR	discharged	41.6 kg/y
ALMR Metal	fuel inventory	2583.8 kg
	discharged	380.4 kg/y
	burned	51.0 kg/y
ALMR Oxide	fuel inventory	2455.0 kg
	discharged	275.9 kg/y
	burned	57.3 kg/y

The amount of transuranics burned per year is about 10-20% higher for the oxide fueled core clue to the lower transmutation rate of U-238 to transuranics. For the metallic fueled design, the ratio of burned TRU fuel per year and TRU fuel inventory is lower than for the oxide fueled design. So, in the oxide fueled design, a higher percentage of TRU is burned per year.

The reduction factors for the A LMR burners for the energy scenario presented above have been calculated with the data presented in Table 3 and with a loss fraction in reprocessing of 0.1 %. In Figure 3, the inventory reduction factors for the TRU mass for the metallic fueled and oxide fueled designs are presented as a function of operation time. These graphs show that the oxide fueled burner performs better in reducing LWR waste. Differences between the reduction factors can be seen only after 50 years, because then LWRS are shutdown instantaneously and from then burners operate autonomously which leads to a fast reduction of the waste. After 250 years of ALMR burner operation, the oxide fueled burner design reduces the TRU mass by a factor of 160 compared to 90 for the metallic fueled burner design.

Three reasons for the difference in performance between the oxide and metallic fueled burners are:

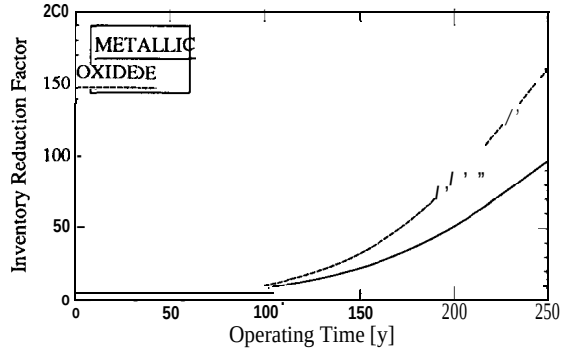

Figure 3: Inventory reduction factor for TRU mass for the metallic fueled ALMR and for the oxide fueled ALMR

- the burned TRU mass is higher for the oxide fueled burner than for the metallic fueled burner,
- the directly deposited waste in reprocessing, which is equal to the loss fraction times the discharged fuel mass, is less for the oxide fueled burner than for the metallic fueled burner for the same loss fraction,
- the total fuel inventory of the oxide fueled burner is less than that of the metallic fueled burner due to the relatively low out-core fuel inventory of the oxide fueled burner.

CONCLUSIONS

In this paper, an alternative to the metallic fueled reference ALMR core is presented, with the same operational characteristics and which fitted in the same geometrical configuration as the metallic fueled core. In this alternative design with mixed oxide as fuel, shielding is less than for the metallic fueled design because of the extra amount of fuel necessary to operate the core. More fuel is needed because of the lower density of the oxide fuel and because of the softer neutron spectrum.

Also, an alternative to the metallic fueled burner ALMR core is presented. The oxide fueled burner produces less TRU waste per cycle at a lower TRU fuel content, but burns more TRU than the metallic fueled burner, due to a smaller fraction of out-core fuel, and a higher average fuel burnup, possible because of lower power peaking and a longer in-core

residence time.

This study shows that when an oxide fueled burner is optimized within the same geometrical configuration and within the same limits and constraints as an optimal designed metallic fueled burner, the oxide fueled burner might perform as well as or even better than the metallic fueled burner.

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