# Application and Economic Feasibility of Functionally Graded Composite For Lead-Bismuth Service



By

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B.Eng., Chemical System Engineering

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Submitted to the Department of Materials Science & Engineering
in Partial Fulfillment of the Requirements for the Degree of
Master of Engineering in Materials Science and Engineering
at the

Massachusetts Institute of Technology
September 2008



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ABSTRACT

Use of materials in liquid Pb/Pb-Bi systems in the higher temperature (550°C-700°C) in advanced liquid metal cooled advanced reactor systems is limited by their corrosion resistance. To address this issue, an Fe-12Cr-2.55Si alloy system is being developed and researched, and when used along with T91 (9Cr-1Mo) as base material, it will be applicable in tubes production mainly for advanced LBE (Lead-Bismuth Eutectic) reactor systems.

An analysis was carried out on this new technology's benefits and its commercialization to evaluate whether or not the technology has economic feasibility if it then is used and commercialized in LBE nuclear industry. The results indicate that this new material has potential to be favored. Before coming to this conclusion, factors such as examination of IP landscape & competing technologies, current and potential of competitiveness of the LBE reactors and the new materials, and a simple business strategic & entry market analysis have been conducted.


Thesis Supervisor: Ronald G. Ballinger

Title: Professor of Nuclear Engineering and Materials Science & Engineering

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# I. INTRODUCTION

## 1.1. LBE Nuclear Reactor

Generation of electricity from fossil fuel, such as natural gas and coal, has been identified as a source of carbon dioxide emission. This emission's effect is called as green house gas effect and fosters global warming and since past few years there have been strong initiative efforts to reduce such effects, by increasing the efficiency of generation and use of the electricity, and even by looking for further alternative clean energy sources such as wind, solar, biomass, geothermal, and nuclear. The later option of using nuclear energy to replace the use of fossil fuel seems to be favored since currently there are 438 nuclear power plants in service worldwide and tends to increase in the future (fig.1) [1]. It provides 17% of world electricity which is the largest share produced by non fossil sources as shown in fig.2. Yet, the use of nuclear is being threatened due to the safety, reliability, and proliferation concerns; however, thanks to R&D, the threat of this issue could be pressed for some extents. Presently the new generation four (Gen IV) of nuclear reactors is being researched and developed. This new system reactor is expected to be able to provide the enhanced safety, minimal waste, and proliferation resistance, and for this envisioned goals, there are six Gen IV reactors' design concepts being developed. One of the designs, Lead-Cooled Fast Reactor, is intensely being developed, and for the best case, it is planned to be deployed in 2025 [3]. For this kind of reactor, Lead-Bismuth coolant was chosen due to the physio-chemical and thermodynamic properties. In addition to its good heat transfer, its low melting point (T=123.5°C) and high boiling point (T=1670°C) provide wide margin in the boiling [4]. Furthermore, its low pressure and chemical inertness of reaction with air and water, will avoid the combustion danger that exist in sodium cooled reactor. These benefits provide the enhancement of safety of Lead-Bismuth Rector.

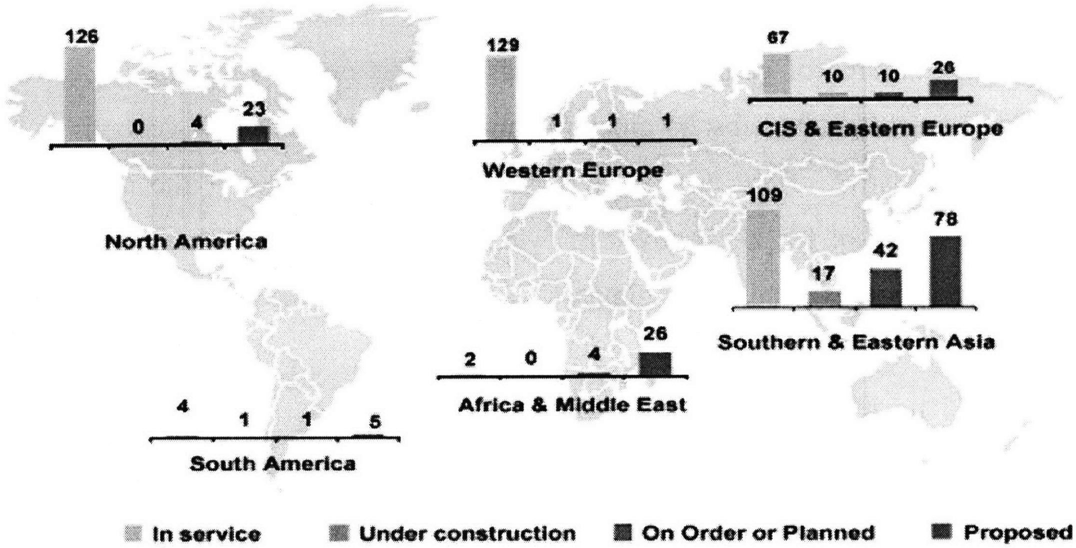



Fig.1. Nuclear Reactor Location [1]

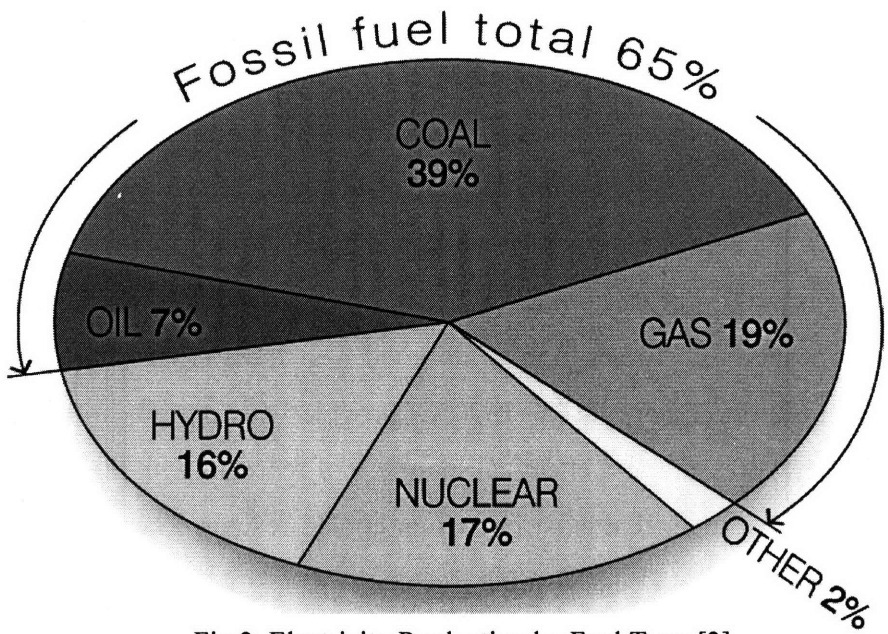



Fig.2. Electricity Production by Fuel Type [2]

## 1.2. Properties of Pb-Bi alloy

Pb-Bi alloy is a binary alloy which has eutectic composition of 44 wt% of Pb and 56 wt% Bi, so called LBE (Lead-Bismuth Eutectic) as a proposed coolant for the Lead-Cooled Fast Reactor, a part of Gen IV reactor initiative [5]. It has low melting point of 123.5°C and high boiling point of 1670°C. Table 1 below shows the more details of Pb-Bi alloys properties.

Table 1. Properties of liquid Pb-Bi alloy [4]

| Liquid Metal | Pb | LBE | Bi | Na |
|---|---|---|---|---|
| Atomic number | 82 | - | 83 | 11 |
| Atomic weight (amu) | 207.2 | ~208 | 208.9804 | 23.0 |
| Melting Point (°C) | 327.5 | 125.5 | 271.4 | 97.8 |
| Boiling Point (°C) | 1750 | 1670 | 1564 | 883 |
| Density ($g/cm^3$ at 600°C) | 10.27 | 9.91 | 9.66 | 0.83 |
| Viscosity (cP at 600°C) | 1.556 | 1.170 | 1.049 | 0.207 |
| Vapor Pressure (mmHg at 600°C) | 0.0004 | NA | 0.08723 | 23.70 |
| Thermal Neutron Cross Section (barns) | 0.17 | 0.094 | 0.034 | 0.53 |
| Chemical Reactivity (with air and water) | Inert | Inert | Inert | Highly reactive |

## 1.3. Advantages and Disadvantages of Pb-Bi alloy.

Due to its good heat transfer, Pb-Bi alloy may be used as spallation targets and heat carriers to shed light for an alternative way to building a new nuclear reactor system. In addition, it provides more enhanced safety with its low melting point and high boiling point, meaning it can avoid risk of coolant boiling at high temperature. Increasing the temperature could improve the thermal and energy conversion efficiency, and potentially allow hydrogen production through thermo-chemical process, thus reducing pollutant emission. In addition, high boiling point allows it to not necessarily pressurize the reactor even at high temperature, improving the safety since it reduces loss of coolant dramatically and allows passively safe designs.

Moreover, unlike sodium, its chemical inertness to the reaction with air and water, would possibly avoid the explosive combustion that exists in a sodium cooled reactor. Capital cost required for building a reactor plant could also be reduced as it would not need any intermediate coolant loop.

Nevertheless, Lead-Bismuth alloy is good option of coolant technology if it is used for lower temperature uses (below than 450°C), that the corrosion phenomena are insignificant. For more advanced nuclear reactor systems such Gen IV nuclear reactors specifically Lead-Cooled Fast Reactor, which is usually operated at higher temperature (above 550°C), Pb-Bi liquid alloy corrodes many important alloys, especially nickel based alloys and steels with nickel as shown by figure 3. Therefore, a new corrosive-resistant material for use in higher temperature LBE reactors is necessary.

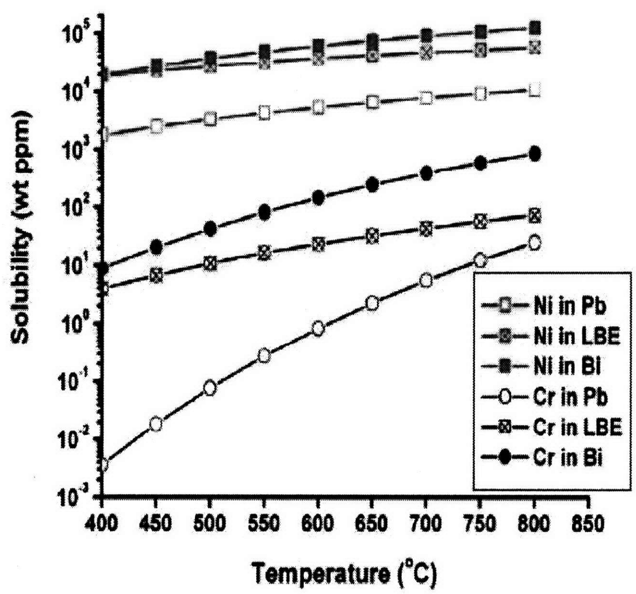



Fig.3. Solubility of Cr and Ni in liquid Pb, Bi and Pb-Bi eutectic [4,6-8]

## 1.4. Purpose and Scope of This Thesis.

This thesis will primarily discuss the development of the new structural material used in LBE nuclear reactors. This new advanced alloy material is expected to resist against corrosion in the temperature above 550°C and up to 700°C, and has good creep rupture and is structurally sound, and should be economic considering commercial quantities.

This thesis also will explore the potential application of this new material mainly in the nuclear industry, as well as other industries, such as chemical and utility industries. It is going to evaluate the competitiveness of this new material, in terms of additional benefit given and its price compared to those of current existing cladding structural materials used in fast reactor nuclear systems. It will assess the continuing of commercialization of this new material and its final product in the future by relating to the future market prospect of its main customer nuclear industry.

## II. TECHNOLOGY REVIEW

### 2.1. Materials Candidate

Gen IV reactor design, here specifically the LBE reactor, envisioned a goal to provide highly economical, safer, proliferation-resistant nuclear power plants. For this advanced Gen IV nuclear reactor, higher operating temperature, above 550°C will be required; unfortunately, current structural materials fail to satisfy the corrosion resistance requirement. For this reason, new structural materials which endure much higher temperature in lead-bismuth environment need to be developed. For the Gen IV and LBE applications, over the range of operating temperatures, stresses, and doses, the materials candidate is desired to have characteristics as follow: (1) adequate mechanical properties (strength, ductility, fatigue, creep, toughness); (2) excellent dimensional stability (resistance to irradiation creeps, void swelling, thermal); (3) favorable radiation resistance under high neutron dose (hardening and embrittlement), (4) adequate corrosion and stress corrosion [9]

To select candidate material systems and its compatibility, several alloys, refractory metals, ceramics, Oxide Dispersion Strengthened (ODS) steels would be discussed.

**Ni based alloys**

Nickel and Nickel alloys are metals with high strength and toughness, excellent corrosion and heat resistance properties. They have been used in many applications, such as steam turbine power plants, nuclear power systems, and chemical industries. It offers excellent corrosion resistance to a wide range of corrosive media, though many factors influence the rate of attack. The new developed Ni based super-alloys, such as IN740 (Ni-2Fe-24Cr-20Co-2Nb-0.5Mo-2Ti-1C) has good mechanical property at high temperature and good creep resistance [9,fig.4].

However, Nickel based alloys have highly solubility in liquid Pb-alloys and its radiation embrittlement, swelling, and phase instability under radiation environment, make the nickel based alloys difficult as resistant materials at higher temperature and higher radiation of LBE reactor system. It is appropriately considered for lower temperature and lower radiation dose of LBE reactor [10].

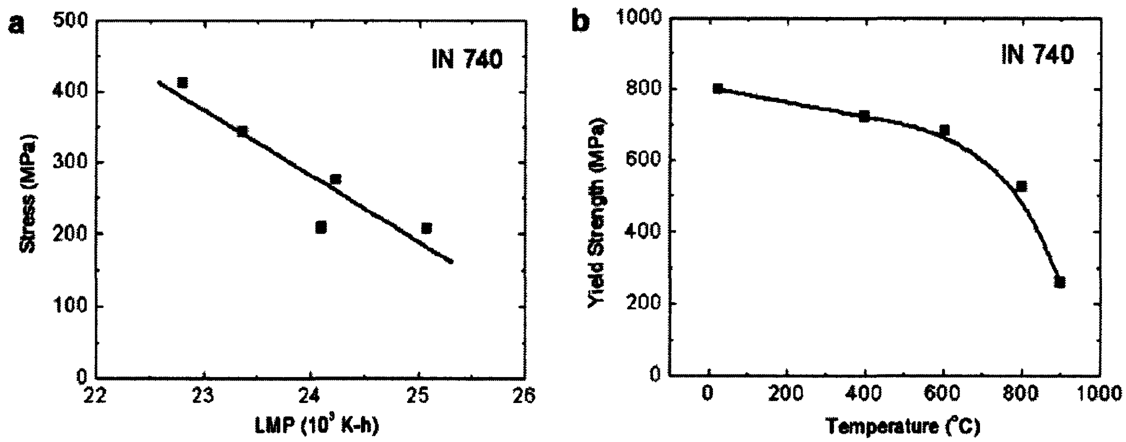



Fig.4. (a) Stress vs LMP Plot, and (b) yield strength as a function of temperature for IN 740 Alloy

**Ferritic-Martensitic (F-M) Alloys**

Generally F-M alloys are alloys with microstructure of Fe and 9-12%Cr. They have good corrosion, void swelling and relatively good creep resistance. Hence, they may be used in some numbers of Gen IV reactors, but its specified application for Lead-Bismuth Reactor System must be further researched since Cr is known to be more soluble than iron in liquid Pb-alloys and its corrosion significantly depends on the oxygen concentration in the liquid metal. In the presence of oxygen, Cr could form chromium oxide which then becoming corrosion protective oxide layer film. It can reduce the penetration/dissolution of Cr into liquid Pb. Nevertheless, in the absence of oxygen, higher corrosion rates have been reported [11,12]. Adding Si/Al into the Fe-Cr alloys is also reported to improve the overall corrosion resistance even at very low oxygen concentration due to the formation of double oxide film (Cr-base and Si-/Al-based) [13-15]. Here, the control of oxygen is necessary and important.

More research is needed to judge the viability of these F-M steels for LBE Gen IV reactor system. The understanding of oxide film and the effect of alloying elements is necessary to find the candidate corrosion resistant materials at LBE environment,

**Austenitic stainless steels**

Austenitic material has good corrosion resistance; however, relatively severe corrosion may occur in certain environments. Austenitic grade stainless steels, such as

316L and AISI 316L, are not corroded at lower temperature of 420°C since thin oxide surface film is formed; however, they fail for exposure at 600°C [9]. When heated to high temperature for certain time, chrome will form chrome carbides at ground boundaries which will then be depleted in chromium. Reducing the chrome available and leads to the losing of its corrosion resistance. This depletion of Cr from the grain boundaries may hinder the applicability of Austenitic stainless steels against corrosion in lead-alloy cooled system. It is noted that swelling in austenitic stainless steel is much higher compared to the F-M Alloys [16].

**Refractory Metals**

The refractory materials, such as Molybdenum (Mo), Tantalum (Ta), Tungsten (W) and Niobium (Nb), have been researched for their application in liquid-Pb alloys. They have very high melting points of 2000°C, and are thus considered as corrosion resistant candidates for higher temperature application. In addition, they have good creep and swelling resistance; however, they are poorly resistant to oxidation and radiation embrittlement. Their economical viability also renders their commercial use as candidate materials for LBE reactor. Refractory metals and alloys are very expensive.

Tungsten, the most abundant of refractory metals with melting point of 3410°C, shows good corrosion resistance at high temperature. But, its poor machinability and high thermal neutron absorption cross-section can increase the cost of fabrication, pushing it cannot be commercialized material for liquid Pb coolant reactor. Tantalum is corrosion resistant at higher temperature in liquid Pb-alloys, but its property of easily being oxidized and high thermal neutron absorption cross-section, hinder future promising application of this metal. Molybdenum, in the absence of oxygen, does not get corroded at temperatures up to 1000°C, but it is brittle under low proton radiation [4].

**Ceramics** [4]

Most nitride, carbide, and oxide ceramics are considered to be compatible with Pb and Bi. Carbides and Nitrides, such as TiC, ZrC, SiC, TiN, and ZrN, are corrosion resistant and suitable for high temperature Lead Fast Reactor components. Graphite is good candidate and can be used up to 1000°C as long as no oxygen is present during operation. Although, ceramics have excellent corrosion resistance at higher temperatures, generally they have very poor mechanical properties (strength, toughness), and are thus not good candidate as structural materials unless used as part of composite or functionally graded material.

**Zirconium Alloys** [9]

Zirconium is commonly used in both light and heavy water reactors because of the satisfactory corrosion resistance at high temperature, low neutron cross section, and favorable mechanical properties (strength, toughness). Below 300°C, and in absence of irradiation, this alloy has the lowest corrosion rate and has been widely used for fuel cladding, pressure tubes, and core internals However, higher temperatures in Gen IV reactors, would limit the application of this zirconium alloys due to its embrittlement because of hydride formation, allotropic phase changes at higher temperature ($\alpha \rightarrow \beta$ phase), creep properties.

**Oxide Dispersion Strengthened (ODS) Steels** [9]

ODS Steels are considered possible structural materials for future generation of high temperature Gen IV nuclear reactor system. They have good mechanical and high temperature resistant property, radiation resistance (swelling and embrittlement). Taking 12YWT (Fe-12.29Cr-3W-0.39Ti-0.248Y2O3) as an example, the oxide of this ODS material hinders the moving dislocation effectively and sinks the radiation induced defects. It also has good creep resistance. Nevertheless, without affecting the total ductility of radiated steels, this material while radiated at lower temperature shows hard hardening, but remarkably less at higher temperature. More research needed on this issue.

Therefore, considering the high solubility of Ni in liquid Pb-alloys, the poor radiation embrittlement of and economic viability of refractory alloys, the poor mechanical properties of ceramics, the embrittlement and hard hardening issue of zirconium alloys and ODS steel at high temperature, leave the primary choice of the candidate materials for Gen IV LBE reactor system to either F-M alloys or Austenitic Stainless Steels as shown in table 2.

Table 2. Summary of Candidate Materials [9]

| Reactor system | F-M steel | Austenitic S.S. | ODS steel | Ni-base alloys | Graphite | Refractory alloys | Ceramics |
|---|---|---|---|---|---|---|---|
| GFR | P | P | P | P | – | P | P |
| Pb-LFR | P | P | S | – | – | S | S |
| MSR | – | – | – | P | P | S | S |
| SFR | P | P | P | – | – | – | – |
| SCWR | P | P | S | S | – | – | – |
| VHTR | S | – | – | P | P | S | P |

P = primary option; S = secondary option.

## 2.2. New Alloy Material

As discussed above, the use of Pb and Pb-Bi eutectic as a coolant for advanced reactor systems (transmutation system designs as well as lead cooled fast reactor systems) has been, to this point, limited by the corrosive nature of the coolant with respect to the fuel cladding and/or structural materials. Corrosion issues have placed an upper limit of approximately 550°C on the operation of these systems. This has provided motivation for a number of alloy development efforts with the aim of raising the upper temperature limit to the 700°C. One of these programs, a collaborative effort between MIT, the Los Alamos National Laboratory and the Idaho National Laboratory, has focused on the development. The development of these materials represents a critical step in the materials area for both transmutation and lead cooled fast reactor systems.

Since higher thermal and radiation resistance and low swelling property of F-M alloys compared to the Austenitic Stainless Steels, here, iron alloys containing Cr and Si (Fe-Cr-Si system) are investigated to shed lights solving corrosion mechanism in iron based alloys as discussed before. The basis of this base chemistry choice is the desire to develop a system that will both form a protective film over a very wide range of oxygen potentials and, at the same time, provide a system that exhibits minimal solubility in liquid metals at oxygen potentials below even the formation potential of $SiO_2$, which may exist in creviced or other oxygen depleted regions that must develop in any engineering system. Iron and Cr have much more limited and finite solubility. Chromium will form a protective oxide film at very low oxygen potentials. Silicon is both very slightly soluble and forms a very protective oxide film at very low oxygen potentials- below that for

Chromium oxide scales. Considering those aforementioned issues, iron alloys with Cr (~18wt%) and Si (~2.5wt%) were selected as the primary materials for investigation, and the combination of the proposed Fe, Cr, and Si composition of those selected alloys are shown in table 3.

Table 3. Proposed composition of selected alloys for Pb-Bi eutectic corrosion tests [4]

| Material | ID | Nominal Composition (in wt%) |
|---|---|---|
| Fe-Si alloys | S1 | Fe-1.25% Si |
| | S2 | Fe-2.55% Si |
| | S3 | Fe-3.82% Si |
| Fe-Cr alloys | C1 | Fe-1% Cr |
| | C2 | Fe-2.25% Cr |
| | C3 | Fe-9% Cr |
| | C4 | Fe-12% Cr |
| | C5 | Fe-18% Cr |
| Fe-Cr-Si alloys | CS6 | Fe-2.25% Cr-0.5% Si |
| | CS7 | Fe-2.25% Cr-1.25% Si |
| | CS8 | Fe-12% Cr-0.5% Si |
| | CS9 | Fe-12% Cr-1.25% Si |
| | CS10 | Fe-18% Cr-0.5% Si |
| | CS11 | Fe-18% Cr-1.25% Si |
| | CS12 | Fe-18% Cr-2.55% Si |

Low concentration of Cr (1~2.25%) in Fe-Cr alloys forms a duplex oxide, outer iron oxide and inner chromium oxide. However, both oxides do not avoid lead Pb alloy penetration during the exposure at 600°C. Increase in Cr concentration fosters the oxidation of Cr to $Cr_2O_3$ initially along the intersection of alloy grain boundaries, then penetrating into the internal oxidation zone. This phenomenon is observed in Fe-9wt% Cr, and less on Fe-12%Cr. Such penetration only takes place if there is insufficient Cr and critical volume of $Cr_2O_3$ particles is inadequate for immediate development of $Cr_2O_3$ layer [17]. Fe-9wt% does not provide adequate protection from LBE penetration. A higher Cr-18wt% concentration results in further change in oxide composite, leading to formation of single oxide layer of $Fe_2O_3$-$Cr_2O_3$ solid solution between $Fe_2O_3$ and $Cr_2O_3$ [4]. It is observed the disappearance of internal oxide zone resulted the solubility of $Cr_2O_3$ has increased significantly on the surface oxide. As a result, to prevent LBE penetration the Cr content should be 12wt%.

Adding Si fosters more protective oxide film at very low oxygen potentials- below oxygen potential scale of chromium oxide. In Fe-Cr alloy with low Cr concentration, only internal (grain boundary) oxidation is observed without any diffusion barrier; however, with higher Cr (12 wt%) concentration in Fe-Cr-Si alloy, Si can serve as an efficient by forming Si oxide beneath the Cr oxide layer. 0.5%Si in Fe-12%Si fails to form desired Si oxide protective layer due to the low concentration of Si [4}. With the increase Si content in the alloy, an increased Si concentration in the oxide layers is observed. Si levels of 2.55 wt% should be sufficient to assure “protection” at even very low oxygen potentials and, at the same time, assure the formation of Si rich, slightly soluble layer at even lower potential oxygen potentials where $SiO_2$ may be unstable.

Eventually, Fe-12%Cr-2.55% Si has been developed, and its protective dual oxide formation (Cr based/Si based) provides a high degree of corrosion protection in Pb and Pb alloy system. In addition, it will enable materials technology for Pb based accelerator driven, lead cooled fast reactor systems and potentially supercritical water systems. Its corrosion resistance has been tested in Pb/Pb-Bi eutectic both at MIT and in the DELTA Loop at Los Alamos National Laboratory (LANL). However, its strength and radiation performance are still being researched and developed but will likely be limited by the Si content. One solution of to the problem will be the production of a functionally graded composite materials consisting of a corrosion resistant layer with a high strength alloy structure component. These materials will have the same characteristic that they will consist of dominant structural layer based on the Fe-Cr-C alloy system, with a surface overlay layer of high silicon ($\geq$2.55 wt%) Fe-12%Cr-Si alloy, added by a 9Cr-1Mo based commercial quenched and tempered alloy as the base structural layer materials.

## III. COMPETING TECHNOLOGY AND IP LANDSCAPE

### 3.1. Competing Technology

High Chromium (9-12%Cr) ferritic/martensitic steels were considered for elevated-temperature in fast reactor application (up to 650°C or higher) for cladding, wrappers, ducts since 1970s due to their thermal and radiation resistance property, and low swelling compared to the austenitic stainless steels.

HT9 is an F-M steel that was developed for power generation industry in 1960s and introduced for fast reactor in the 1970s. Since then, several improved F-M steels, offering significant improvement for HT9, are developed for power generation industry. Below Table 4 shows the evolution of five developed and being developed ferritic/martensitic steels.

Table 4. Evolution of Ferritic/Martensitic Steels for Power-Generation Industry [18]

| Generation | Years | Steel modification | $10^5$ h rupture strength (MPa) | Steels | Maximum use temperature (°C) |
|---|---|---|---|---|---|
| 0 | 1940–60 | | 40 | T22, T9 | 520–538 |
| 1 | 1960–70 | Addition of Mo, Nb, and V to simple Cr-Mo steels | 60 | EM12, HCM9M, HT9, HT91 | 565 |
| 2 | 1970–85 | Optimization of C, Nb, and V | 100 | HCM12, T91, HCM2S | 593 |
| 3 | 1985–95 | Partial substitution of W for Mo and addition of Cu | 140 | NF616, E911, HCM12A | 620 |
| 4 | Future | Increase W and add Co | 180 | NF12, SAVE12 | 650 |

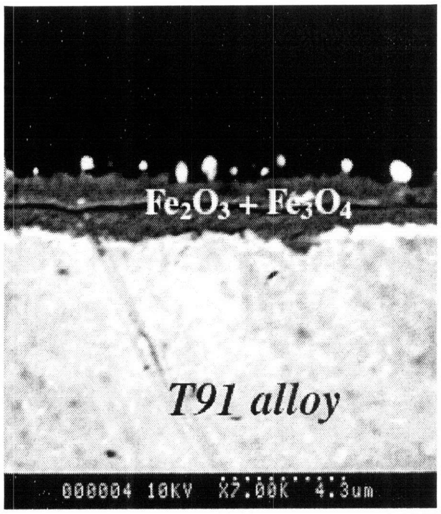
The second generation modified of HT9 ferritic-martensitic steels is modified 9Cr-1Mo (T91). The word modified refers to addition of Nb and V in order to improve the creep strength. It has shown improved irradiation properties. Higher Cr content in T91 promotes higher performance, better irradiation embrittlement resistance, and preferred alternatives for components that must withstand higher faster neutron effects. T91 has been commercialized and currently most of fast nuclear reactors use T91 as their structural materials for cladding. Nevertheless, the maximum use temperature of T91 is 593°C, above this temperature corrosion will occur.

For applications to 620°C, the third generation of NF616 and HCM12A were developed in Japan, and E911 developed in Europe. NF616A and E911 have almost the same composition with T91, while W is added into E911 and some of Mo is replaced by W in NF616 [18]. Experiments on T91, HCM12A, and NF616 have been conducted. They were radiated at 300°C in the mixed neutron spectrum of high flux reactor (HFR), and that properties of T91 are superior for the new steels both before and after radiation [19]. Tensile test showed that NF616 least hardened, followed by T91 and HCM12A hardened the most. The ductile to brittle transition temperature increases in all three alloys; however, T91 develops larger shift in this transition temperature.

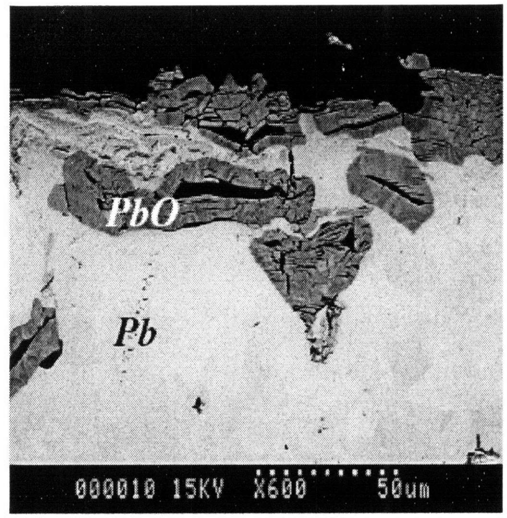
The future fourth generation of ferritic-martensitic alloys are developed recently by increasing the W and adding the Co content, such as NF12 and SAVE12. Nevertheless, this fourth generation materials which contain Co, are not suitable for nuclear use.

Hence, the discussion here for the competing technology will focus on T91, which is superior and applicable in the use of coolant reactor until certain temperature. Indeed, in the market this steel is the most preferable structural cladding materials used for nuclear industry. Nevertheless, significant microstructural changes of T-91 occurs when exposed to temperature higher than 550°C during operation in LBE reactor system as it gets corroded. One important issue for T-91 to be competing technology to our new composites is that it costs cheaper compared to new our developed materials.

Nevertheless, based on corrosion test done by A. Maitre et.al for T91 steel in lead or lead-bismuth liquid bath, a porous corrosion layer ≤ 5 microns, is observed on transverse section of the T91 sample immersed in liquid lead at 350°C (fig.5)



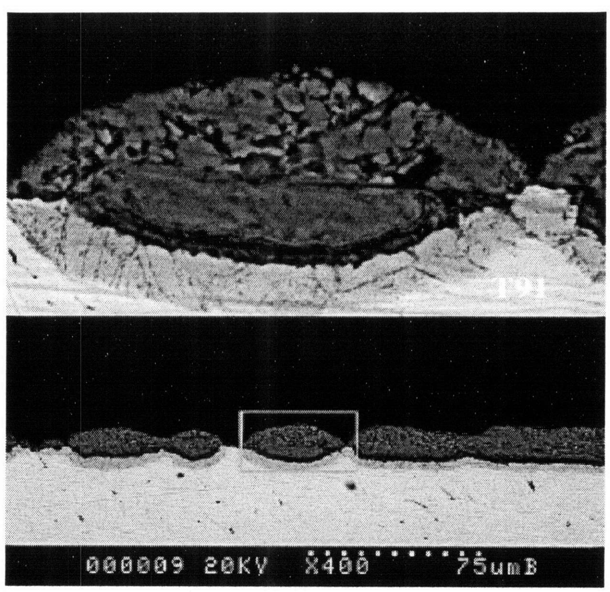
(a)



(b)

Fig.5. Cross sections of the oxide layers on T91 steel (a) and lead (b) [20]

At the highest temperature, 600°C, a duplex corrosion layer, (1) an iron depleted transition layer of about 5 μm and (2) a Fe(Fe(1-x)Crx)2O4 porous layer is observed in fig.6 [20]



(a)

Fig.6. SEM pictures of the corrosion layers formed at 600°C at the interface T91/liquid Pb-Bi [20]

## 3.2. IP Landscape

Our functionally graded composite is one of the most important technologies determining the continuing of generation four nuclear reactor system (LBE reactors). Currently, patents regarding on materials with high corrosion and creep resistance used in lead-bismuth coolant do not exist. Yet, there are several patents regarding on the materials used in coolant technologies, besides lead-bismuth coolant. Here are several patents discussing corrosion resistive material at elevated temperature, but in different coolant technologies.

1. Coated structural component for a high temperature nuclear reactor (Helium Coolant) Patent#: 4190493, Feb 26, 1980 by Kim. S. Yee of Sulzer Brothers Limited.

**United States Patent** [19] [11] **4,190,493**

**Yee** [45] **Feb. 26, 1980**

[54] **COATED STRUCTURAL COMPONENT FOR A HIGH TEMPERATURE NUCLEAR REACTOR**

[75] Inventor: **Kim S. Yee**, Zurich, Switzerland

[73] Assignee: **Sulzer Brothers Limited**, Winterthur, Switzerland

[21] Appl. No.: **862,422**

[22] Filed: **Dec. 20, 1977**

**Related U.S. Application Data**

[63] Continuation of Ser. No. 660,862, Feb. 24, 1976, abandoned.

[30] **Foreign Application Priority Data**

Feb. 26, 1975 [CH] Switzerland ........................ 2420/75

[51] **Int. Cl.**[2] ............................................ **B32B 15/00**

[52] **U.S. Cl.** ...................................... **176/60**; 176/88; 204/38 S; 428/663; 428/665; 428/680; 428/926

[58] **Field of Search** .................... 176/88, 60; 428/660, 428/665, 680, 663, 926; 204/38 S

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*Primary Examiner*—Arthur J. Steiner

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[57] **ABSTRACT**

A protective layer of tungsten or molybdenum is tightly adhered via an intermediate layer of pure nickel to a substratum of nickel-base alloy containing a carbide-former. The protected substratum is used in the structural components for a helium cooling circuit of a high temperature nuclear reactor. The protective layer is of a thickness of from 0.5 to 0.2 millimeters while the intermediate layer is of a thickness of 0.01 to 0.05 millimeters.

**4 Claims, No Drawings**

For high temperature nuclear reactors, helium is commonly used. However, the medium circulating in the cooling circuits generally contains small quantities of impurities, for example, water and/or hydrogen which react with the graphite of the reactor to form carbon monoxide and methane. In addition, the ordinarily-used nickel-based alloys for the structural parts of this primary circuit contain alloying additives, titanium and chromium. Both of these, especially in the case of the high temperatures of some 1000°C, prevailing in these circuits, react with the carbon of the carbon-containing impurities, and through carbonizing and forming carbide, lead to deterioration of the mechanical characteristics of the nickel-base alloys. Material comprising of, (1) a substratum of Ni-base alloy, 0.02 to 0.15% C, 5.5 to 16% Cr, 3 to 13% of the sum of Mo and W, 6 to 11% of the sum of Al and Ti and the remainder being Ni; (2) a 0.01 to 0.05 millimeters of intermediate layer of Nickel of at least 99% purity, and (3) on top of it, a 0.05 to 0.2 millimeters of pore-free protective of W/Mo layer done by CVD process, is expected to provide a protective layer for structural components used in high temperature nuclear reactors (operated at temperature between 800°C and 1200°C) which is able to prevent carbonization of the base material, to form a protective layer on nickel base alloys against oxidation.

2. Nuclear Reactor Component Cladding Material (Water Coolant)
   Patent#: 2871176, March 2, 1956 by Joseph E. Draley, Clarendon Hills, Weslty E. Ruther of U.S. Atomic Energy Comission

**2,871,176**

**NUCLEAR REACTOR COMPONENT CLADDING MATERIAL**

**Joseph E. Draley, Clarendon Hills, and Westly E. Ruther, Skokie, Ill., assignors to the United States of America as represented by the United States Atomic Energy Commission**

**Application March 2, 1956, Serial No. 569,215**

**11 Claims. (Cl. 204—193.2)**

Aluminum has excellent corrosion resistance and its usage as one of the primary metals of commerce to the barrier oxide film that is bonded strongly to its surface, and that if damaged, re-forms immediately in most environments. Nevertheless, it happens only at temperature approximately 200°C. At temperature 200°C and above, at which transition in corrosion behavior of aluminum takes places, aluminum is corroded against of interaction with water. Aluminum is not suitable used in water coolant nuclear reactor system operated at elevated temperature of above 200°C as it will be corroded correspondingly at accelerated rate. For these reasons, new material of binary alloy of Al, contains between 2% and 4% Ni was researched and developed as base material to form corrosion resistance cladding for fuel elements and coolant tubes. It has been found that an alloy of aluminum and nickel is not subject to corrosion by water at temperatures up to 350°C, and is therefore suitable for use in water-cooled reactors in which the water may attain a temperature of over 200°C. It has been found that a small amount of iron included in the alloy makes it possible to reduce the amount of nickel to a point where the total neutron capture cross section of the alloy is reduced while retaining the desired corrosion resistance. Therefore, for optimum results in a reactor a ternary alloy of aluminum, nickel and iron may be employed.

### 3.3. Impact on Business Strategy

Currently patents on the technology development of structural material which is resistant against corrosion in lead-bismuth coolant environment in the temperature above than 550°C do not exist. It is an advantage for us as our new technology material is a pioneer in this field. And, if we are going to patent our invention, it is a better idea to include points to make the patent as broad as possible. Methods of its fabrication, types of elements and their content required for this new material, types of environment where it is corrosion resistant (lead-bismuth alloy coolant and probably supercritical water at temperature of 550°C-700°C) should be discussed.

Once filing the patent is done, a business model could be developed. This pioneer patent in this patent technology development, gives us much benefit as we do not have competing technology, as well competing companies. This may lead us to be able to monopolize the market in near future; however, for long term it is very difficult to predict, especially lead fast reactor nuclear as our main customer currently is being researched and developed, and still takes long time to be commercialized. During this period, it might appear the other new technologies would compete with our current new technology.

After patenting, there is a possibility of licensing this technology to other corporations, especially start-up companies. However, this would be determined based on further analysis of the market. It is based on the market of our nuclear industry as our main customer and the pipe & tube industry. The market of nuclear industry in near future would be discussed in the next chapter.

By starting up a company, if our pipe's selling price is competitive and comparable enough with its provision of additional benefits, and if there is earning potential to commercialize the new tubes in the market, the decision would not to be license out the technology, but continue to build a company that would profit from this business. If then the company were growing to a large enough size, it may be possible for the company to produce the tubes not only for the nuclear industry, but also for variety industries, including chemical and utility industry. However, if at the time, the market holds too many competitors to achieve significant portion of the industry, then the decision would be to license out the technology and obtain the profit from the licensing, considering the chance of earning percentage of the each pipe sold.

## IV. FUTURE NUCLEAR MARKET FOR GENERATING ELECTRICITY

### 4.1. Nuclear Power Generation Industry

Concerns over energy security, surging fossil-fuel prices and rising $CO_2$ emissions make people are looking other alternative energies. Nuclear power along with solar & wind power arise in the discussion about their potential to become important sources of energy in the future. However, solar and wind power can satisfy only limited supply needs so that the nuclear power may suitable to answer the current concern over energy security, surging fossil-fuel prices and rising $CO_2$ emissions.

The principles of nuclear power generation are relatively the same as for thermal power generation. Water is boiled and the emitted steam is used to power turbines for generating electricity. Nuclear power is a result from energy created through nuclear fission using uranium whereas generating thermal power relates with burning coal, natural gas, or oil.

### 4.2. Global Shift to Nuclear Power Generation

After 15 years in decline, nuclear energy is back on the agenda due to climate change and energy security concerns. Nuclear power is a proven technology for large-scale base-load electricity generation that can reduce the dependence on imported gas and $CO_2$ emissions and improve security of supply. Another plus point is that uranium which is used for nuclear power generation process is abundant and widely distributed around the world. From the economic point of view, nuclear power is highly cost-competitive with coal and gas where the price of these commodities is soaring.

(1) Rising energy demand

Demand of energy is dependent on economic growth. Report from World Bank and International Energy Agency shown that for every 1% of GDP growth the world consumes 1.2% more energy. This varies by region where for developed countries such as for N. America & Europe consumes around 1%, for Middle East around 2.5% and for Latin America around 2% [21]. Furthermore, the rising economy of China and India will increase further the energy demand.

Table 5. Major Countries – GDP Growth Rates, 2000-2011 [21]

**Major Countries GDP Growth (YoY change) (2000-2011E)**

| | 2000 | 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008E | 2009E | 2010E | 2011E |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| US | 3.8% | 0.3% | 2.4% | 3.0% | 4.2% | 3.2% | 3.3% | 2.2% | 0.8% | 0.9% | 2.7% | 2.7% |
| Japan | 2.4% | -0.3% | 0.2% | 2.5% | 2.7% | 2.6% | 2.2% | 2.1% | 1.7% | 1.0% | 1.6% | 2.0% |
| Euro Zone | 3.5% | 3.2% | 0.8% | 0.5% | 1.7% | 1.4% | 2.8% | 2.6% | 1.3% | 1.1% | 2.0% | 2.0% |
| Germany | 3.1% | 0.7% | 0.2% | -0.1% | 1.1% | 1.1% | 3.0% | 2.6% | 1.3% | 1.0% | 2.1% | 1.7% |
| France | 4.2% | 1.8% | 1.2% | 0.5% | 2.1% | 1.2% | 2.1% | 1.9% | 1.2% | 0.9% | 2.0% | 2.3% |
| Italy | 2.9% | 1.8% | 0.4% | 0.4% | 1.0% | 0.1% | 1.9% | 1.6% | 0.5% | 1.2% | 1.2% | 1.3% |
| UK | 3.1% | 1.9% | 2.0% | 2.2% | 3.2% | 1.9% | 2.8% | 3.2% | 1.4% | 1.3% | 2.6% | 2.8% |
| Sweden | 3.7% | 1.4% | 1.9% | 1.6% | 3.5% | 2.4% | 4.5% | 2.6% | 2.1% | 2.0% | 2.3% | 2.3% |
| China | 8.0% | 7.3% | 8.0% | 9.1% | 9.5% | 9.9% | 10.7% | 11.4% | 9.8% | 9.30% | 10.0% | 9.8% |

In line with the promising outlook of GDP growth in major countries (table 5), global electricity demand is expected to increase from 64GW per year during 2005 – 2010 to 95GW per year during 2020 – 2025 as shown in fig.7 below.

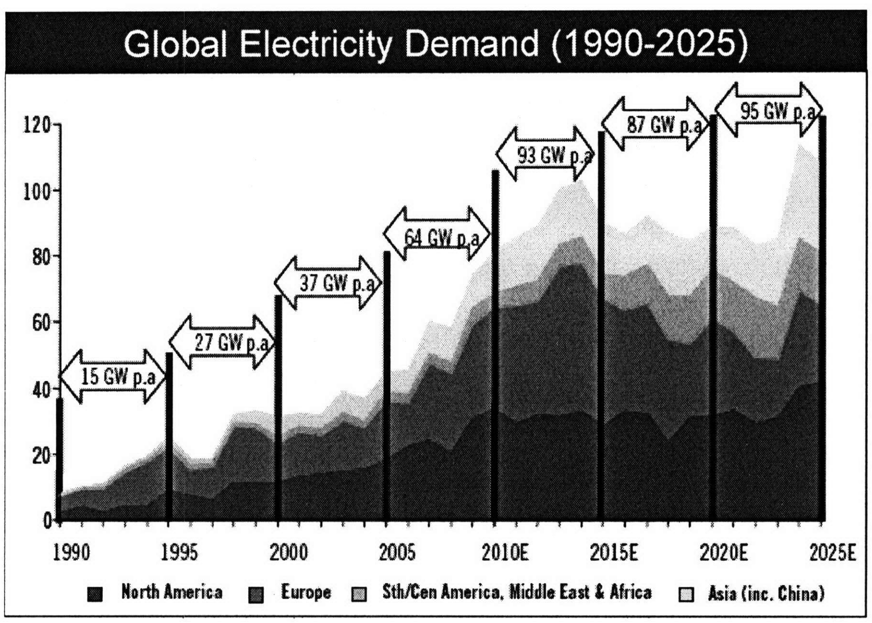


Fig.7. Global Electricity Demand [22]

(2) Supply of energy security

In Europe, the dependency of imported energy resources is high, estimated around half of the region's energy resources demand. The tendency is likely to rise from 50% to

70% in the next 20-30 year later [23]. Most of Europe's imported energy is from Gulf region and Russia which is politically unstable countries that can any time result into energy supply shortage. Another concern is the high level of oil price which is continuously rising from early 2003 to present (fig.8). In July 2008, NYMEX Light Sweet Crude Oil Price was reaching above $140/BBL.

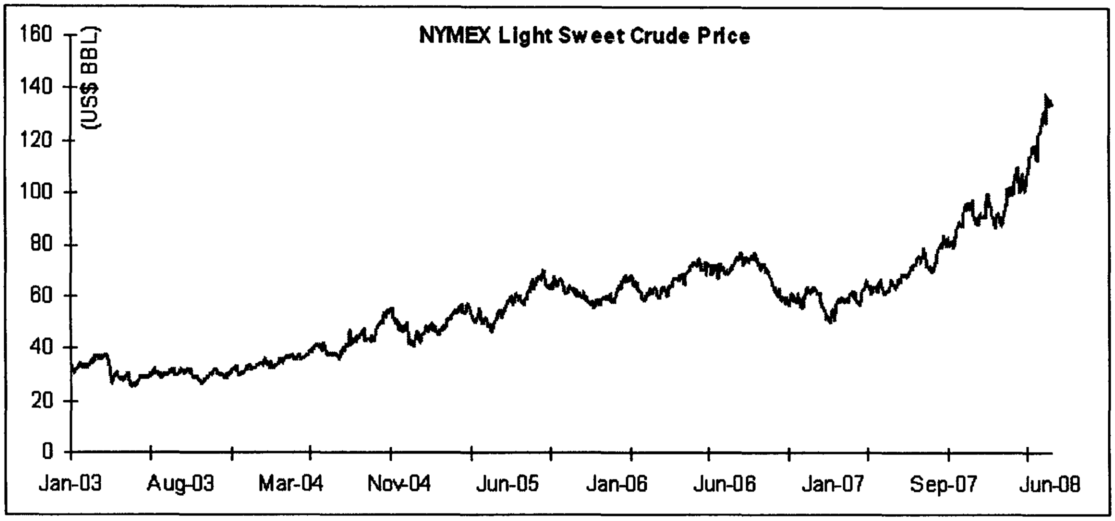


Fig.8. Fluctuation of Crude Oil Price [56]

Current oil and gas reserves are expected to last another 40 and 60 years respectively and should reach their peak in about 15 to 20 years. Coal reserves are expected to last for some hundreds of years; however, these are polluting and thus dangerous. On the other hand, uranium which is used for nuclear power generation process is abundant and it has been identified that there are 4.8 million tons of uranium resources widely distributed around the world and 10 million tons undiscovered (table 6). Current estimated uranium resources indicate that there are resources for at least 200 years of supply at current rates of consumption and even in the case of massive expansion of nuclear energy.

Table 6. Uranium Resources [22]

| Uranium Resources (in million tons) | | | | |
|---|---|---|---|---|
| | Conventional | | | |
| | Identified (deposits) | | Undiscovered | |
| Cost of recovery $/kgU | Reasonably Assured Resources (RAR) | Inferred resources (1) | Prognosticated resources (2) | Speculative resources (3) |
| <40 | 1.95 | 0.8 | 1.7 | 4.6 |
| 40 to 80 | 0.7 | 0.36 | | |
| 80 to 130 | 0.65 | 0.29 | 0.82 | |
| > 130 | - | - | ? | 2.9 |
| Subtotal | 3.3 | | 2.52 | 7.5 |
| General total | 4.8 | | 10.0 | |
| | General total conventional resources: 14.750 000 tonnes<br>World demand in 2006: less than 70,000 tonnes<br>Resources: > 200 times 2006 demand | | | |
| | With Gen 4 Fast Breeder Reactor, resources are virtually unlimited | | | |

(1) geological evidence; (2) indirect geological evidence; (3) extrapolated values

Furthermore the uranium price is expected to decline due to increased mining therefore increased supply and declining uranium price as shown in fig. 23. This may result lower production cost generating power.

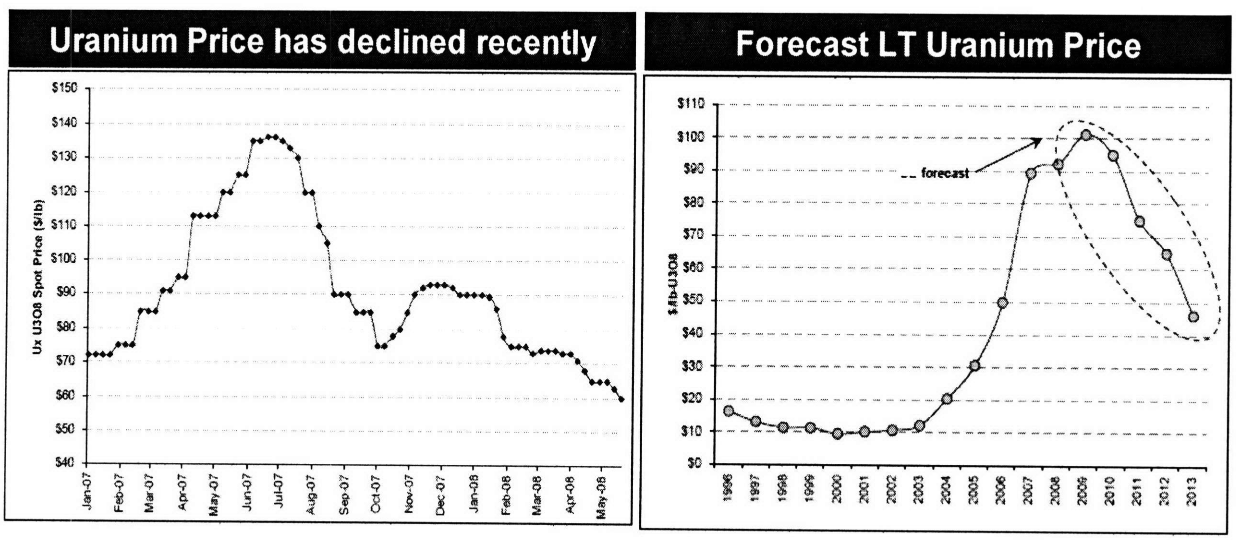


Fig.9. Historical and Projected Uranium Prices [23]

(3) Cost competitiveness.

Because coal and gas fired generation types have significant $CO_2$ exposure, nuclear energy as electricity generation source is becoming an option. Nuclear is highly cost competitive with coal and gas. Though nuclear plants have high capital cost and average O&M (operating and maintenance) cost, but it has very low fuel cost compared with the coal and gas, which then makes their generation cost relatively very low (fig.10).

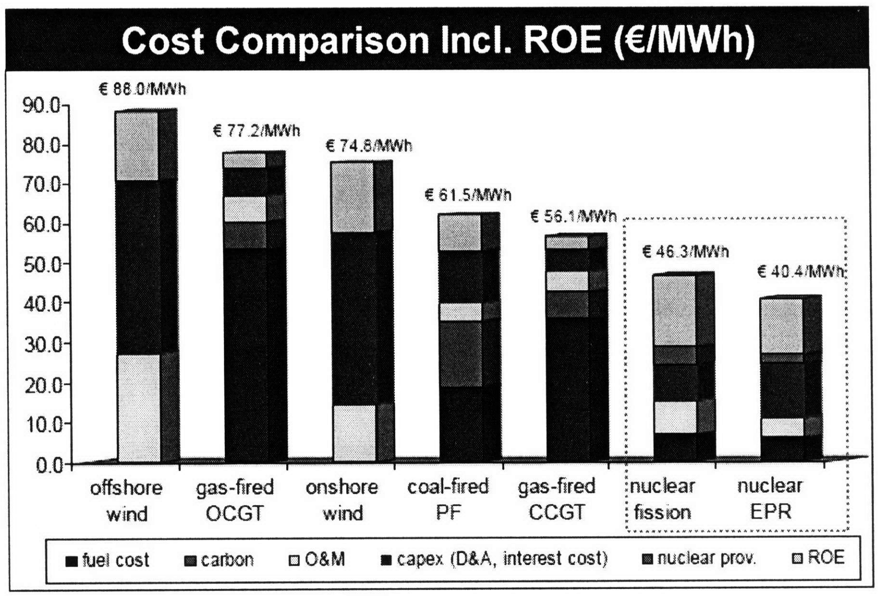


Fig.10. Comparison of Cost Generating Electricity with Different Sources [22]

(4) Climate Change

"Kyoto Protocol" & Alternative Energy to Reduce $CO_2$ & Greenhouse Gases

Global warming and abnormal weather phenomena are discussed intensively these days. Efforts are being made to regulate $CO_2$ and other greenhouse gases as well as efforts to achieve the numerical targets contained in the Kyoto Protocol and the accompanying emission trading system and Clean Development Mechanism (CDM).

The "Kyoto Protocol" was adopted at a meeting of the 3rd Conference of the Parties in Kyoto in December 1997. It covers six types of greenhouse gas: carbon dioxide, methane, nitrous oxide, HFCs, PFCs, and sulfur hexafluoride. The protocol targets a reduction in emissions of these gases to the 1990's levels which to be achieved over 2008-12. The emission reduction targets by region are 6% for Japan, 8% for the 15 EU countries, and 7% for the US (which has since withdrawn from the protocol) (table 7). Total of 169 countries have ratified the agreement.

Table 7. Greenhouse Gas Emission Restrictions Based on Kyoto Protocol [22]

**Kyoto Protocol: Greenhouse Gas Emission Restrictions**

| Country | Emission of greenhouse gas ($CO_2$ conversion million tons) | | Increases and decreases in emission (compared to 1990) | | | Ratification |
|---|---|---|---|---|---|---|
| | 1990 | 2000 | As of conference | Reduction rate by signature | Net | |
| Japan | 11.9 | 13.4 | 13% | -6% | -19% | Yes |
| America | 61.3 | 70.4 | 15% | -7% | -22% | No |
| Germany | 12.5 | 10.1 | -19% | -8% | 11% | Yes |
| England | 7.4 | 6.5 | -13% | -8% | 5% | Yes |
| Canada | 6.1 | 7.3 | 19% | -6% | -25% | Withdrew |
| Russia | na | na | -38% | 0% | 38% | Yes |

The Kyoto Protocol expires in 2012 and the effort to formulate a post - Kyoto successor protocol for setting the emission reduction targets for the next commitment period will start in 2008. Moreover, developing countries such as China and India, which were not part of the Kyoto protocol, are likely to participate in the next international mechanism. Successor to Kyoto Protocol are likely to have tougher numerical targets, requiring both Japan and US to substantially reduce greenhouse gas emissions.

As shown in fig.11, nuclear power emits the least amount of carbon dioxide when compared to the other alternatives so that it may be used as an alternative energy to reduce greenhouse gases emission so that it would comply with Kyoto Protocol.

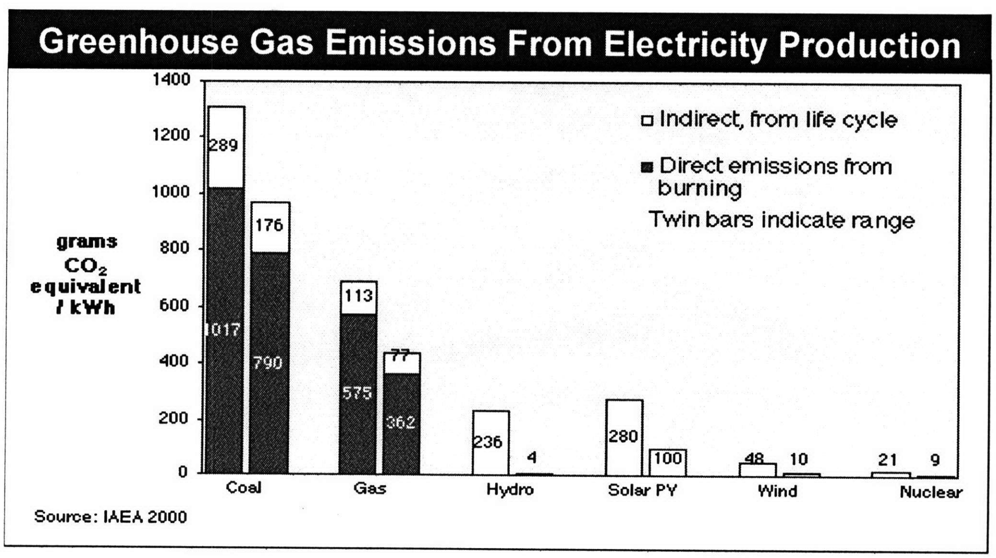


Fig.11. GreenGas House Emission from Different Energy Sources [2]

Although there are many positive impacts of nuclear reactors, yet there are still negative risks of them. The safety of the nuclear energy is being questioned as it potentially causes severe accidents, though in many cases human error can not be ruled out. For its security, there is threat that it could be used for military and terrorist purposes. There is also issue of how to dispose nuclear waste in a way that does not pose hazard to human health is still hardly resolved. Nevertheless, Gen IV nuclear reactors exist to solve these negative issues. Though it cannot fully eliminate the existence of these risks, the Gen IV reactors are expected to reduce the occurrence of those risks.

Considering above terms regarding on the climate change, energy security and low-cost electricity of nuclear energy, it is strongly predicted the future of nuclear industry in near future is bright. The negative risks of nuclear reactors are expected to decrease due to provision and envisioned benefits of Gen IV reactors.

## V. COMPETITIVENESS OF LBE REACTOR SYSTEM

### 5.1. Overview of Present Liquid Metal-Cooled Reactors (LMRs) and Lead-Cooled Fast Reactors (LFRs) Worldwide

Initially, the feasibility of nuclear reactors with fast neutrons was recognized in the 1940, which EBR-1 in the USA was the first reactor delivering the first electrical current produced through fission processes. Afterwards, the development of fast reactors started in several countries, notably in USA, USSR, UK, France, in the late 1940s, including reactors such as CLEMENTINE and EBR-1 in the USA, and BR-2 in the USSR. Subsequently, from 1950s to early 1970s, experimental reactors such as EBR-2, Fermi, and FFTF (USA), BR-10, and BOR-60 (USSR), Rapsodie (France), KNK-II (Germany), JOYO (Japan), FBTR (India), and DFR (UK) were constructed, which then leading to prototype power reactors such Phonix (France), PFR (UK), BN-350 (USSR-KAazakhstan), BN-600 (USSR-Russia), MONJU (Japan), and PFBR (India) (table 8) [24,26]]. These high power fast neutron reactors are normally cooled by liquid metal such as sodium, lead or lead-bismuth, which has high conductivity & boiling point and no moderating effect. Nevertheless, among these Liquid Metal-Cooled Reactors (LMRs), the ones to use lead/lead-bismuth as their coolant were mainly developed by Russia, Pb-208, BREST, and SVBR. Lead/lead-bismuth cooled alloy reactors in several regions would shortly discussed in the following.

**Russia** [24-26]

The use of fast lead/lead-bismuth coolant reactors is dominated by Russia. Russia used lead-bismuth cooling for 40 years initially for LFR reactor, OK-550 and BM-40A, capable of producing 155MW, applied for Alfa class submarines. The significant new design is the BREST-300 fast neutron reactor, 300 MWe or more with lead as its primary coolant at 540°C. The smaller and newer Russian design is the Lead-Bismuth Fast Reactor (SVBR)-75/100 of 75-100 MWe with Pb-Bi alloy as its coolant at 400-480°C. These designs based on the reactor experience with submarines, and could be used for electricity production, sea-water desalination, and utilization and transmutation of actinides.

**Japan & Korea** [24-26]

Japan's lead-bismuth cooled fast reactor design is Japan's LSPR with 150 MWt/53MWe. The super-safe, small, and simple-L-4S'nuclear battery' system is being developed by Toshiba and CRIEPI in collaboration with STAR work in USA. It uses Pb-Bi as its coolant at temperature of 510°C. In addition, JAEA (Japan Atomic Energy Agency) proposed ADS (Accelerator Driven System) to construct a lead-bismuth eutectic cooled fast reactor with 800 MWth. These R&D activities were conducted during 2005, to investigate the feasibility of the ADS as the accelerator, lead-bismuth eutectic as core coolant. Following Japan, KAERI (Korea Atomic Energy Research Institute) also proposed ADS system, called HYPER (Hybrid Power Extraction Reactor) with the lead-bismuth eutectic is planned as its coolant.

**USA** [24-26]

There is not enough data regarding on lead-cooled fast reactors in USA. It seems that present U.S. Policy is focused upon on deployment of large scale Light Water Reactors and sodium-cooled fast spectrum. Nevertheless, U.S. is participating actively in Gen IV reactor development plans, and is currently focusing on lead-cooled fast reactors (LFR), in addition of gas cooled fast reactors and small modular sodium cooled fast reactors.

Table 8. Fast Neutron Reactors [26]

| | | | |
|---|---|---|---|
| **USA** | | | |
| EBR 1 | 0.2 | | 1951-63 |
| EBR 2 | 20 | | 1963-94 |
| Fermi 1 | 66 | | 1963-72 |
| SEFOR | 20 | | 1969-72 |
| Fast Flux TF | | 400 | 1980-93 |
| **UK** | | | |
| Dounreay FR | 15 | | 1959-77 |
| Prototype FR | 270 | | 1974-94 |
| **France** | | | |
| Rapsodie | | 40 | 1966-82 |
| Phenix | 250 | | 1973- |
| Superphenix 1 | 1240 | | 1985-98 |
| **Germany** | | | |
| KNK 2 | 21 | | 1977-91 |
| **India** | | | |
| FBTR | | 40 | 1985- |
| **Japan** | | | |
| Joyo | | 140 | 1978- |
| Monju | 280 | | 1994-96-? |
| **Kazakhstan** | | | |
| BN 350 | 135 | | 1972-99 |
| **Russia** | | | |
| BR 5 /10 | | 5/10 | 1959-71, 73 |
| BOR 60 | 12 | | 1969- |
| BN 600 | 600 | | 1980- |

## 5.2. Competitiveness LBE Among Other Gen IV Nuclear Reactors

Examining the competitiveness of LFR reactors to the other Gen IV reactors, in this chapter the comparison of LFR and the other five Gen IV nuclear reactors would be discussed. According to the technology roadmap of nuclear reactors, it is known that Gen IV is the latest design of nuclear reactors which have envisioned goals to be economical, safe and proliferation resistant (fig.12). There are six system designs selected for development of Gen IV, which are (1) Very-High-Temperature Gas-Cooled Reactor (VHTR), (2) Sodium-Cooled Fast Reactor (SFR), (3) Gas-cooled Fast reactor (GFR), (4) Lead-Cooled Fast Reactor (LFR), (5) Molten-Salt Reactor (MSR), (6) Super-Critical Water-Cooled Reactor (SCWR) [3,27-28].

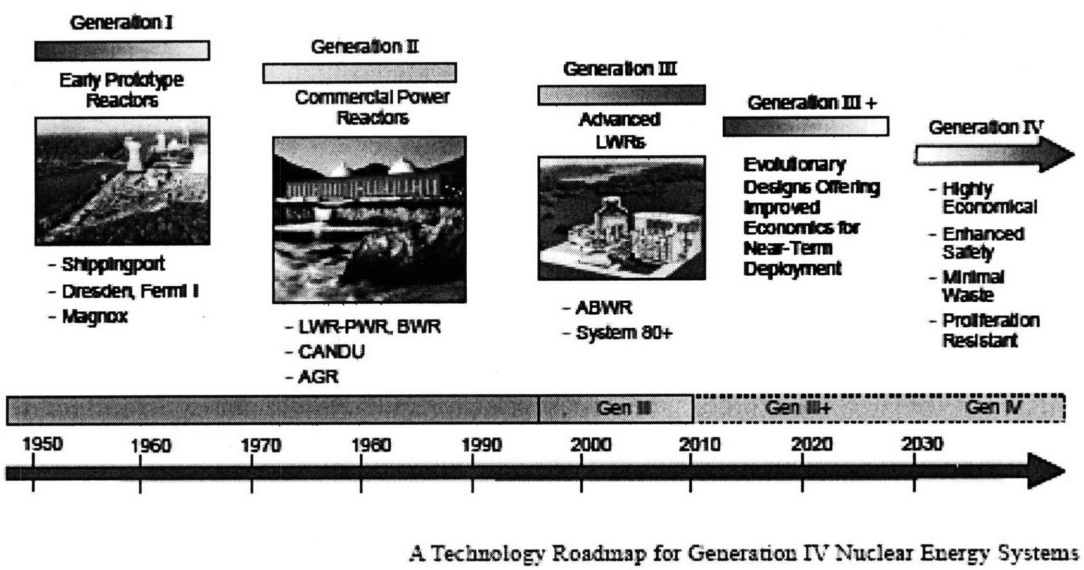


Fig.12. Technology Roadmap for Gen IV Nuclear Reactors [3]

5.2.1. Overview of Gen IV Nuclear Reactor Systems

(1) Very-High-Temperature Reactor System (VHTR)[27-29]

The VHTR is a graphite-moderated, helium-cooled reactor with high efficiency, over 50% at core-outlet temperature of 1000°C. This high core outlet temperature will enable nuclear heat application for efficient hydrogen generation and to other industrial processes. For electricity generation, the VHTR is an attractive heat source for large industries, including refineries and petrochemical industries to substitute large amounts of process heat at different temperatures, because it can be arranged as a direct cycle system. VHTR systems were highly ranked in economics because of their high efficiency of hydrogen production and the inherent features of this reactor increase the safety and reliability. Due to the open fuel cycle, the VHTR is good in proliferation resistance and physical protection.

(2) Sodium-Cooled Fast Reactor System [27-29]

This kind of reactor system is to design an advanced fast neutron reactor, with primary mission is for electricity production and actinide management. Its features are fast-spectrum reactor and closed-fuel recycle system (excellent actinide management including and resource extension). The range of plant size is wide, ranging from modular system to large reactors of 1500–1700 MWe. The smaller reactors would use uranium-plutonium-minor-actinide-zirconium metal alloy fuel supported by a fuel cycle based on pyrometalurgical processing. The larger ones would use mixed uranium-plutonium oxide fuel supported by advanced aqueous processing. It is good in safety, economics and in proliferation resistance and physical protection

(3) Gas-Cooled Fast Reactor System [27-29]

The GFR system features a fast-spectrum helium-cooled reactor and closed fuel cycle with primary deployment would be electricity production and actinide management, but it could also support hydrogen production. It is rated good in sustainability, safety, economy, and in proliferation resistance and physical protection due to closed fuel cycle and actinide management. Through the combination of a fast-neutron spectrum and full recycle of actinides, GFRs minimize the production of long-lived radioactive waste isotopes. The GFR's fast spectrum also makes it possible to utilize available fissile and fertile materials more efficiently than thermal spectrum gas reactors. In addition, it assumes an integrated, on-site spent fuel treatment and refabrication plant.

(4) Lead-Cooled Fast Reactor System [27-29]

LFR systems are Pb or Pb-Bi alloy-cooled reactors with a fast-neutron spectrum and closed fuel cycle. Its primary mission is to generate electricity, hydrogen production, and actinides management. It is highly ranked for safety, economics, sustainability due to closed fuel cycle, and good proliferation resistance due to long-life cores. Similar with SFR, this has several size of plant ratings, including battery ranging (50–150 MWe), a modular system (300–400 MWe), and a large monolithic plant at 1200 MWe which then provide a range of energy products. The LFR battery option is designed to meet market opportunities for electricity production on small grids, and for developing countries that may not wish to deploy a large fuel cycle infrastructure to support their nuclear energy systems. The small size, reduced cost, and full support fuel cycle services of the LFR battery can be attractive for these markets.

(5) Molten Salt Reactor System [27-29]

MRS is a type of Gen IV nuclear reactor with the primary coolant is a molten salt. It operates at low pressures and coolant temperatures up to above 700°C with output of 1000MWe. Due to large number of subsystems it is not highly ranked in economics, but it is good in safety, proliferation resistance, and sustainability because of closed fuel cycle, and excellent actinide management. The molten salt fuel flows through graphite core channels, producing a thermal spectrum, then the heat is transferred to a secondary coolant system through an intermediate heat exchanger, and then through another heat exchanger to the power conversion system.

(6) Supercritical-Water-Cooled Reactor System [27-29]

SCWRs are Gen IV reactors using supercritical water as the working fluid, operated at high-temperature, high-pressure water-cooled reactors that operate above the thermodynamic critical point of water (374°C, 22.1 MPa or 705°F, 3208 psia). Its primary mission is for electricity production and also for actinide management as an option. Because of the thermal efficiency and plant simplification, this reactor system is economic, and also rated good in safety and in proliferation resistance. If the fast spectrum SCWR can be developed it would be also ranked high in sustainability. Depending on the core design, it may have a thermal or fast-neutron spectrum. The efficiency of a SCWR can approach 44%, compared to 33–35% for LWRs. The fuel cycle option for the thermal option is a once-through uranium cycle.

5.2.2. Comparison of LFR and Other Gen IV Nuclear Reactor Systems

Table 9 shows the feature characteristics of each reactor designs of Gen IV nuclear reactors. The fast reactor type of LFR has superior advantage which it has high burn-up and long operation period. In addition, the fast reactor could be used for breeding fissile materials from fertile (U238 and Pu240), utilizing the enormous U238 reserve which opens the prospect of virtually non-exhaustible source of energy. The natural self-protection and passive safety properties are special to this reactor due to the chemical inertness, low melting point and high boiling point of lead-bismuth coolant, closed fuel cycle, as well as integral design of the pool type primary circuit equipment. In addition, it has wide size options of plant ratings, battery ranging (50–150 MWe), a modular system (300–400 MWe), and a large monolithic plant at 1200 MWe which then provide a range of energy products [3]. This variation of size options, especially the small size, is favorably since it can satisfy the customer needs to meet market opportunities for small electricity production, as well as markets in developing countries. In addition to the reduced cost, it would also make it possible to fabricate the whole reactor at the factory and deliver it in practical readiness by using any kind of transport. Shown on table below, the application of lead alloy LFR reactor generates efficiently not only electricity, but also hydrogen and actinide management in the higher temperature, giving additional benefits, compared to the other nuclear Gen IV Nuclear Reactor, especially supercritical water reactor (SCWR).

Table 9. Gen IV Nuclear Energy Systems [29]

| | Neutron Spectrum | Fuel Cycle | Size | Applications | R&D |
|---|---|---|---|---|---|
| Gas-Cooled Fast Reactor (GFR) | Fast | Closed | Med | Electricity, Actinide Mgmt., Hydrogen | Fuels, Materials, Safety |
| Lead-alloy Fast Reactor (LFR) | Fast | Closed | Small to Large | Electricity, Actinide Mgmt., Hydrogen | Fuels, Materials compatibility |
| Sodium Fast Reactor (SFR) | Fast | Closed | Med to Large | Electricity, Actinide Mgmt. | Advanced Recycle |
| Very High Temp. Gas Reactor (VHTR) | Thermal | Open | Med | Electricity, Hydrogen, Process Heat | Fuels, Materials, $H_2$ production |
| Supercritical Water Reactor (SCWR) | Thermal, Fast | Open, Closed | Large | Electricity | Materials, Safety |
| Molten Salt Reactor (MSR) | Thermal | Closed | Large | Electricity, Actinide Mgmt., Hydrogen | Fuel, Fuel treatment, Materials, Safety and Reliability |

The envisioned goals of Gen IV systems are defined in four areas: sustainability, economics, safety and reliability, and proliferation resistance and physical protection. Below is a table 10 showing potential of each system to meet the Gen IV goals. It seems that LFR reactor is competitive enough to compete with other generation four reactors. In terms of sustainability, the LFR system is top-ranked in sustainability because of closed fuel cycle, and in proliferation resistance and physical protection because of long-life cores. In addition, as aforementioned this kind of nuclear reactor is conceived to be based on using natural fissile material uranium-235 and increasing the amount of fissile material by converting uranium-238 (or thorium-232) into fissile materials. The creation of fissile materials in LFR is competitively high and it can maintain the long term availability of systems. Moreover, the transmutation waste of this nuclear reactor is very high. The LFR is expected to minimize and manage their nuclear waste and long term burden in the future; therefore, improving protection for the public health and the environment. In terms of economics, it has clear cost advantage, generating not only electricity, but also hydrogen and actinide management. Even in the last few years Russian publications indicated that LFR is cheaper to build than any other reactor type and the electricity generation cost is lower than that of gas fired plants (table 9) since LFR do not need intermediate coolant loop and thanks to its inherent safety. Another reason making LFR more economical is compared to the SFR, there is less concern about water or air ingress or leaks. In terms of safety, as mentioned before LFR's inherent characteristic provides additional passivity protection (high boiling point and inertness of lead coolant). Though currently LFR is still in the R&D stage, the technical success of this reactor is feasible. More details about the potential of LFR to meet Gen IV envisioned goals can be looked in table 12.

Table 10. Economic Comparison of LFR, SFR and gas-fired plant [48]

| Energy system considered | SVBR-75/100 LFR | BN-800 SFR | Gas PGU-325 |
|---|---|---|---|
| Number of plants x power ($MW_e$) | 16 x 102 | 2 x 890 | 5 x 325 |
| Efficiency of the net plant (%) | 34.6[a] | 46.2 | 44.4 |
| Specific capital investments ($/kW, price of 1991) | 661.5 | 783.4 | 600 |
| Cost of electricity (cent/kWh, price of 1991) | 1.46 | 1.56 | 1.75 |

Table 11. Potential of each system to meet the different Gen IV goals [28]

| **Generation-IV goal** | **VHTR** | **SFR** | **GFR** | **LFR** | **SCWR** | **MSR** |
|---|---|---|---|---|---|---|
| Efficient electricity generation | Very high | High | High | High | High | High |
| Flexibility: availability of high-temperature-process heat | Very high | Low | High | Low | Low | Low |
| Sustainability: creation of fissile material | Medium/low | High | High | High | Low | Medium/low |
| Sustainability: transmutation of waste | Medium | Very high | Very high | Very high | Low | High |
| Potential for 'passive' safety | High | Medium/low | Very low | Medium | Very low | Medium |
| Current technical feasibility | High | High | Medium/low | Medium | Medium/low | Low |

Table 12. Potential of LFR to meet Gen IV Goals [30]

| ***GEN IV Goal Areas*** | ***Goals for Generation IV Nuclear Energy Systems*** | ***Goals achievable via*** | |
|---|---|---|---|
| | | ***Lead inherent features*** | ***Specific engineered solutions*** |
| ***Sustainability*** | Resource utilization. | • Lead is a low moderating medium.<br>• Lead has low absorption cross-section. **Error! Bookmark not defined.**<br>• This enables a core with fast neutron spectrum even with a large coolant fraction. | • Breeding ratio close to 1 |
| | Waste minimization and management. | | • Great flexibility in fuel loading including homogeneously diluted MA. |
| ***Economics.*** | Life cycle cost. | • Lead does not react with Water.<br>• Lead does not burn in air.<br>• Lead has a very low vapor Pressure.<br>• Lead is cheap. | • Reactor pool configuration.<br>• No intermediate coolant loops.<br>• Compact Primary System.<br>• Simple design of the reactor internals.<br>• Supercritical steam (high efficiency). |
| | Risk to capital (Investment protection). | | • Small reactor size.<br>• Potential for in-vessel replaceable components |
| | Operation will excel in safety and reliability. | Lead has:<br>• very high boiling point;<br>• low vapor pressure;<br>• high shielding capability for gamma radiation;<br>• good fuel compatibility and fission product retention. | • Primary system at atmospheric pressure.<br>• Low coolant ΔT between core inlet and outlet. |
| ***Safety and Reliability.*** | Low likelihood and degree of core damage. | Lead has:<br>• good heat transfer characteristics;<br>• high specific heat and thermal expansion coefficient;<br>• core with inherent negative reactivity feedback. | • Large fuel pin pitch.<br>• Decay Heat Removal (DHR) in natural circulation.<br>• Natural circulation cooling (small system).<br>• Primary pumps in the hot collector (moderate- or large- size system).<br>• DHR coolers in the cold collector. |
| | No need for off site emergency response. | • Lead density is close to that of fuel; no risk of re-criticality in case of core melt.<br>• Lead retains released fission products. | |
| ***Proliferation Resistance and Physical Protection.*** | Unattractive route for diversion of weapon-usable material. | • Lead system neutronics enables long core life. | • Small system features sealed, long-life core.<br>• Use of a MOX fuel containing MA increases Proliferation Resistance. |
| | Increased physical protection against acts of terrorism. | • Primary coolant chemically compatible with air and water operating at ambient pressure. | • Independent and redundant DHR loops operating in natural circulation. |

## VI. BUSINESS STRATEGY

### 6.1. Our Product

The purpose of developing the new material (Fe-12%Cr-2.55%Si) is to support and provide new structural materials (cladding, wrappers, etc) used in Liquid-Bismuth Eutectic (LBE) nuclear reactor. The new material, or we can say the functionally graded composites, consisting of a corrosion resistant layer on a structural alloy will produced in 2 forms (1) tubing suitable for piping applications (larger pipe) and (2) tubing suitable for fuel cladding applications (smaller tubing) as shown in fig.13. These product forms will be fabricated using standard commercial practice and commercial vendors will be used for piping/tubing production. Since the new alloy is mechanically not strong enough, the two kinds of new tubes below, have T91 (9Cr-1Mo) as base material, with inner corrosion cladding layer of new alloy for the larger tube and outer corrosion resistance cladding for the smaller one.

Combining T91 and the new alloy in its fabrication, the fabricated pipes/tubes are predicted to have higher cost compared with the current used tubes/pipes in fast nuclear reactors. Currently, T91 tubes are favored to use in commercialized fast nuclear reactor industries as this ferrritic-merritic steel has high strength, good creep structure, and corrosion resistance until certain temperature. However, in the higher temperature above 550°C, as discussed before in liquid Pb-alloy environment, T91 tubes are discovered to suffer severe corrosion as the attack/penetrating of Pb/Bi.

Therefore, our pipe/tube products should be examined whether with the higher cost required will provide comparable additional benefits. Our products are expected to be applicable for liquid Pb/Bi environment up to temperature of 650°C -700°C.

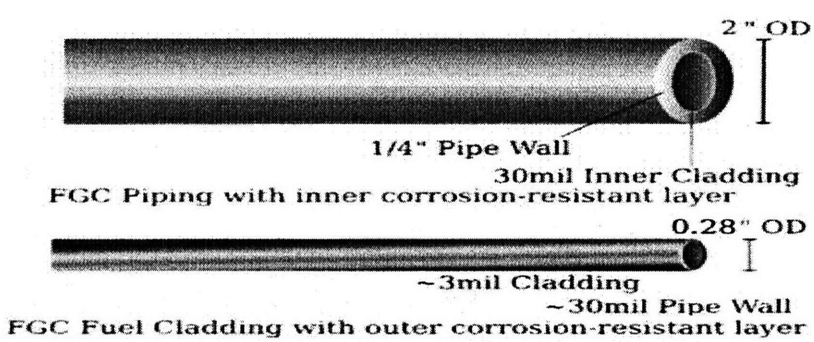


Fig.13. Coolant Piping & Fuel Cladding [31]

## 6.2. Fabrication Method

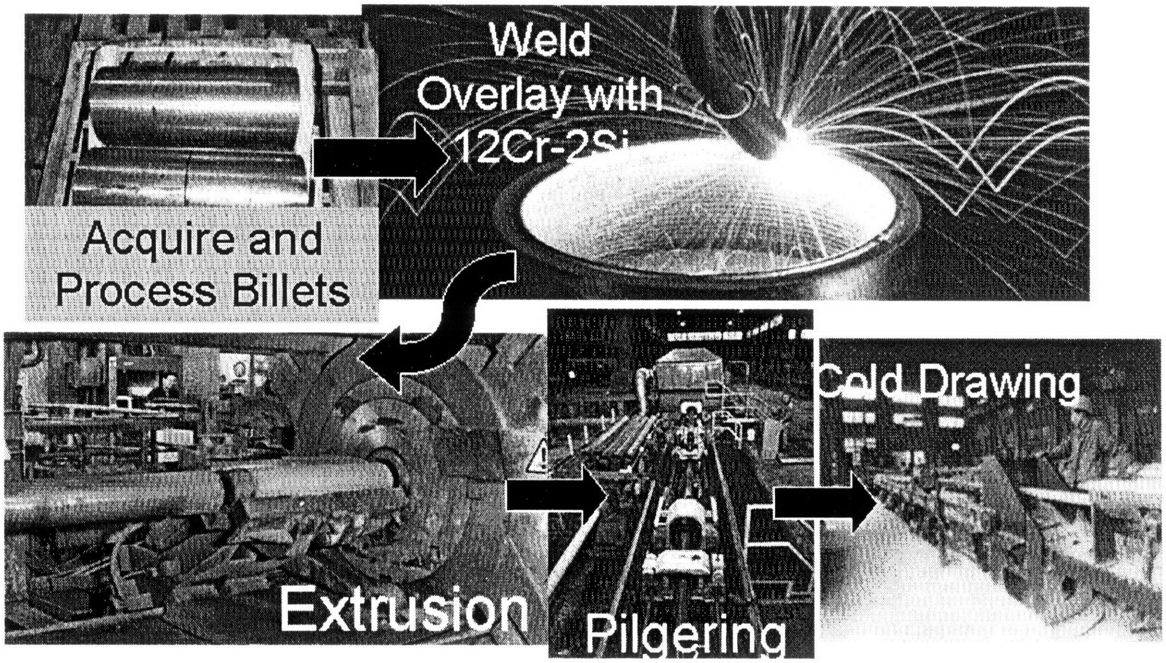


Fig.14. Schematic of Fabrication Process of New Product [32]

Fig.14 shows a schematic of the development steps to produce the cladding product form along with the commercial vendor for each process step. All processing steps will be carried out using commercial melt practice as well as commercial processing facilities. In the first step an extrusion billet is produced either by direct melting. The extrusion billet will then undergo initial processing by extrusion. The result of this process will be a so-called TREX (tube reduced extrusion) which will have the general dimensions of approximately 50 mm diameter, 12 mm wall thickness by length. The TREX will then be overlay welded using welding wire with the desired chemistry for the barrier layer. The weld overlay process is a standard industry practice for the production of many forms of corrosion resistant layered tubing, in particular for the fossil power industry. Such techniques are cost effective and are used for the production of large quantities (> 10,000 meters) of tubing at one time. After weld overlay the TREX will be pre-machined to achieve the desired ratio of cladding to structural layer thickness such that upon final processing the product will be a tube with a 10.16 mm OD/1.016 mm wall product with a 0.2 mm barrier layer. After pre-machining the TREX will be reduced to final dimensions by a series of draws and intermediate annealing steps. The final process steps will be a solution anneal/quench and temper step for the conventionally processed tubing and a special heat treatment for the material.

## 6.3. Potential Applications

(1) Nuclear Industry [18,33-34]

Our project goal is to provide development of materials technology for lead based accelerator driven, lead cooled fast reactor systems and potentially supercritical water systems. Mainly industry benefiting from the production of this kind of new pipes is nuclear industry. They will use our pipes for coolant piping (larger tube) and fuel cladding (smaller tubing). Coolant is a fluid which flows through a device in order to prevent its overheating, transferring the heat produced by the device to other devices that utilize or dissipate it. Our larger tubes will be used to flow that coolant fluid, which in our case is lead-bismuth coolant. Furthermore, in nuclear reactors, cladding is the outer layer of the fuel rods, standing between the coolant and the nuclear fuel. Fuel cladding tubing which is made of a corrosion-resistant material may be used to support that function.

(2) Chemical and Utility Industry [35-39]

Fe-12%Cr-2.55%Si is expected to have corrosion resistance at temperature range of 600°C-700°C in the liquid-Pb alloys. In less corrosive environment, it is expected to have corrosion resistance at higher temperature than 700°C, due to the presence of Si and Cr, providing double oxide protective layer. In addition to the corrosion resistance, the structural alloy mechanical property of this new alloy is promising. Particularly, Cr concentration has been discovered guaranteeing the best corrosion and swelling resistance, as well as minimum embrittlement. In addition, it was found that the steels containing above than 9wt% are reasonably resistant to corrosion [40], swelling [41], and less brittle [42]. Conducted tensile test to Fe-Cr alloys, the presence of Cr in Fe-12%Cr-2.55%Si, influence its hardening phenomenon. Hardening is higher in Fe-Cr alloys than in pure Fe, and a higher hardening rate is discovered for Fe-12Cr alloy which is almost same with out alloy composition (fig.15). Based on above superior features of the new Fe-12%Cr-2.55%Si developed material, it can be used as structural materials at elevated temperatures in the chemical, petrochemical and fossil fired power generating industries. Its high temperature resistant properties and non-destructive evaluation of Fe-Cr-Si lead its possible application for steam generator applications. In addition, heat pipe technology and chemical boilers for application in chemical and utility reactors might benefit this new material.

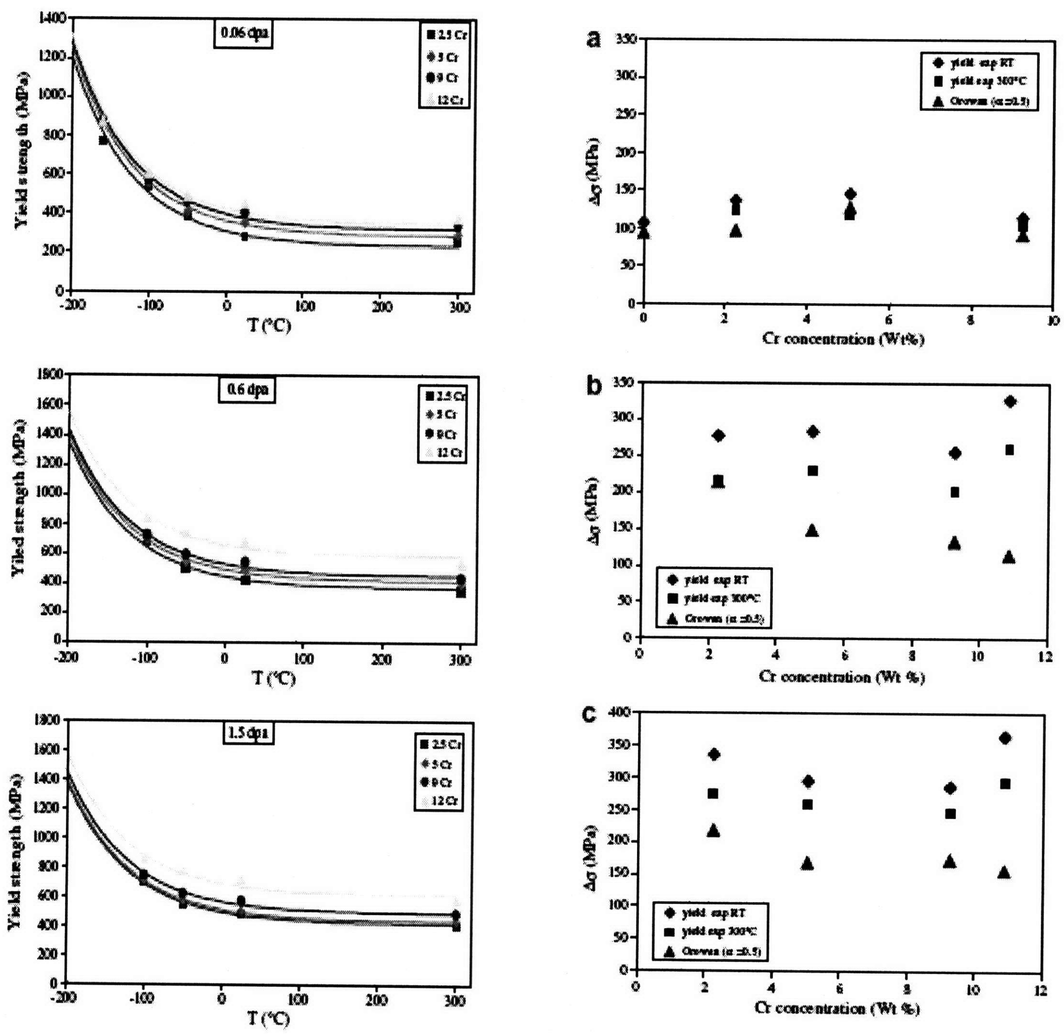


Fig.15. Yield strength dependence on temperature for different Cr content (left), predicted hardening estimated as a function of Cr concentration after irradiation to (a) 0.06 dpa and (b) 1.5 dpa [43]

## 6.4. Supply Chain

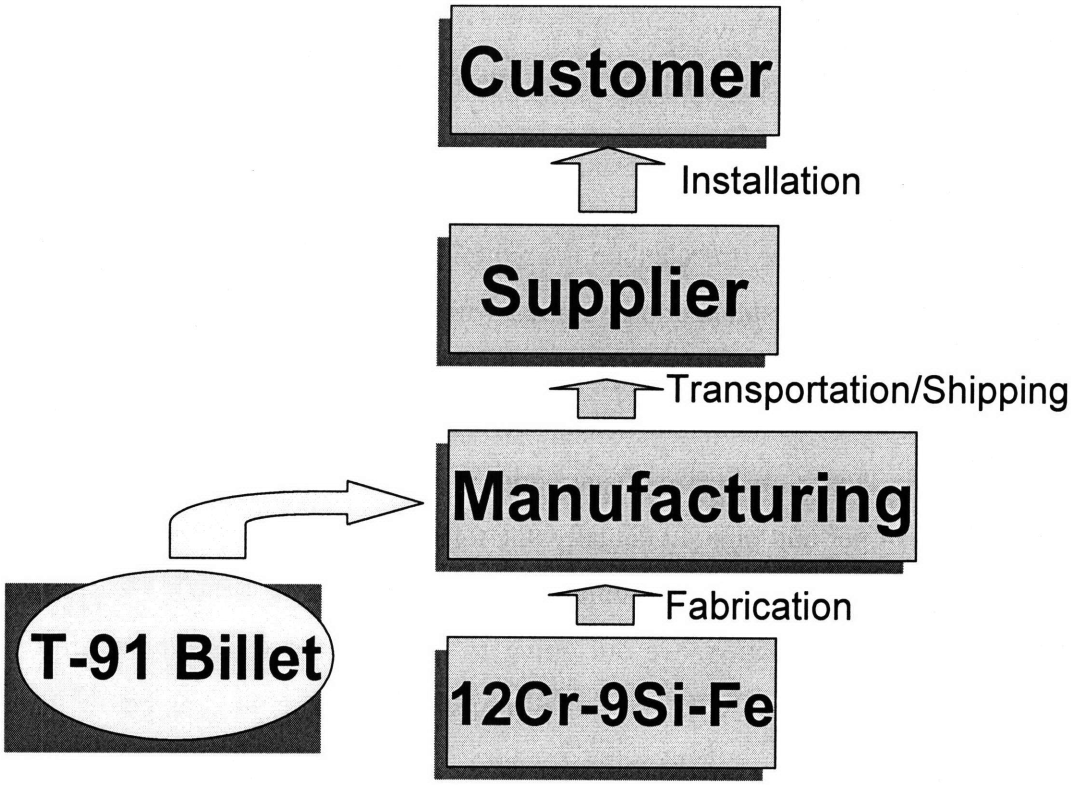


Fig.16. Schematic of Proposed Supply Chain

The supply chain of our products is similar to that of other tube companies. As figured by fig.16, we start the supply chain from material issues. Here, to accelerate the fabrication process, instead of processing the T-91 (9Cr-1 Mo) alloy from its basic elements, we just buy the ready T91 material billet according to the market price, and combine it with our new functionally graded composite (12Cr-9Si-Fe) material, to fabricate the desired tubes/pipes. It is not fully integrated supply chain, and probably risky as our production cost would depend on the market selling price of the T91 alloy, as it also would rely on the price of the basic elements of T91. Nevertheless, in addition to time issue, as just starting up the company, we would like not to invest much in another technology development, besides our new functionally graded composite material development,

## 6.5. Competitiveness of The Product's Price

Based on the supply chain, the base material of T91 is bought from outsiders based on the market price. From reliable source, the price of T91 per lb is $5. To fabricate one 20-25 feet of 2'OD pipe with 0.25'width, 35.14 lb of T91 material is needed (density of T91=8080 kg/m$^3$) [44]. Hence, the material cost of T91 required for one 20-25 feet of 2'OD pipe is $491 per unit pipe.

Since inside the pipe, 3 mil of the new material is cladded, so that the amount of material needed is 35.14 lb. Here, to calculate the material cost of the new material, the new material elements are approximated to be similar with those of alloy 405; therefore it is assumed to have same price with alloy 405 (density of alloy stainless steel 405=7750 kg/m$^3$) [45]. From the alloy calculator of metalprices.com, the price per lb of stainless steel 405 is $0.51 [46]. Hence, the approximated price of the new material to be cladded inside the pipe is $18.14 per unit pipe. Eventually, the total price of material cost for T91 and the cladding material is $509~$510 per unit pipe.

Departing from this calculation, we are going to estimate the feasibility of this project if one piping company is built. The initial project cost is estimated as below in table 13.

Table 13. The Proposed Initial Project Cost

| | |
|---|---|
| Project Cost | |
| Machine Cost | $436,000.00 |
| Welding machine & etc | $400,000.00 |
| Extrusion machine | $16,000.00 |
| Cold drawing machine | $20,000.00 |
| Land (=500m2)+Land Building Cost(0.5 of Land Cost) | $290,655.00 |
| Maintenance (10% of Land & Building Cost) | $29,065.50 |

Besides above initial project cost, the production cost which annually occurs also exists. This production cost consists of variable cost and fixed cost. The variable cost includes material cost and energy cost, while the fixed cost includes labor cost and selling expense and G&A (General and Administrative Cost).

From the technology roadmap guide for Gen IV reactors by U.S. DOE Nuclear Energy Research Advisory Committee, it is known that our main customer, lead bismuth nuclear reactor, has not been ready for commercialization, its prototype is being researched and developed, and this will happen until 2025.

Table 14. The deployment date of each Gen IV nuclear reactor for best case [3]

| *Generation IV System* | *Best Case Deployment Date* |
|---|---|
| SFR | 2015 |
| VHTR | 2020 |
| GFR | 2025 |
| MSR | 2025 |
| SCWR | 2025 |
| LFR | 2025 |

As shown by table 14 above, after year 2025 the LBE reactor is expected to be ready for commercialization and readily generate electricity starting from 2045. Hence, for our business strategy, until 2025 it is predicted there are not many LBE reactors will be built. For initial project, we are starting to fabricate 2000 tubes from year 2009, afterwards production volume will decrease 3% until 2025 since it is assumed that not every year there will be new LBE nuclear reactors. From 2026, since the starting of commercialization of the LBE reactors, it is predicted the industry will need our pipes. Therefore, our production volume returns back to the initial one with the 3% growth of production from year 2026. Our company will only operate until 2045 since we are predicting there will be a new generation (fifth generation) of nuclear reactors would replace the Gen IV LBE reactors.

Based on this plan, we start our production from year 2009 and estimate the production cost for year 2009 is as below (appendix 8-9)

Material cost= $510/unit pipe

Energy Cost= $20.8/unit pipe

Labor Cost= $7.50/unit pipe (will reduce as the production volume increases)

Selling expense and G&A= $ 3.75 /unit pipe (assumed to be half of the fixed cost)

The above fixed and variable cost will increase with 3% inflation rate. The inflation rate is taken to more accurately calculate the real cost as this project takes very long time.

**Assumption:**

The working capital to pay the initial expense each year for this manufacturing company is 7.50 % of revenues.

The depreciation and amortization last for 26 years (from year 2009 to year 2045)

The funding is from equity 30% with expected return of equity 11.4% and from loan 70% with loan rate 6%. The repayment of loan will last for 5 years.

Based on above scenario and assumptions, we are trying to find out the threshold selling price, meaning the price where we get the NPV to be zero. It is obtained that the threshold selling price is $614.26/unit pipe, but the break even takes long (15.92 years). We are aiming the breakeven to be short, expecting the breakeven can be obtained approximately within 3 years. By modeling the spreadsheet of cost analysis, we obtain that to get the 2.98 years breakeven, we should sell the tube/unit with price of $790 ((appendix 10-11). Here, our profit is expected to be $175.74/unit.

Continuing, we are going to examine the competitiveness of our product by selling the new pipe with the selling price of $790/unit pipe. As aforementioned, the commercial price of T-91 tube is $491/unit pipe. Considering the value of our new tubes which is corrosion resistance in higher temperature up to 700°C, from A.V. Zrodnikov et.al in journal "Innovative Nuclear Technology Based on Multi Purpose Lead-Bismuth Cooled Fast Reactor", it is known that increasing temperature up to 650°C will provide increase the reactor's thermal power by 20% without changing the reactor design and cost [42]

From the technology roadmap of Gen IV reactors guide, LBE reactors have thermal power of 125-400 MWth (Pb-Bi battery), ~1000 MWth (Pb-Bi module), and 3600 MWth (Pb large) [3]. Its thermal efficiency is 42% [48], the generation cost of nuclear electricity is $2.03 cents/W (capital cost) [48], and 1.46 cents/W (operating cost) with total cost $3.49 cents/W [49]. The generated nuclear electricity may be sold in price of $8.96 cents/W [50].

Here, taken as example one of LBE reactor with 700 MWe, this reactor needs 2271 tubes. Thus, the obtained value may be achieved by the increase of thermal power as we use the higher corrosion resistant new tube, and the excess cost the nuclear companies might pay while using our new pipes instead of using the T91 pipes is summarized on the table below.

| | |
|---|---|
| The Additional Obtained Value | $7.66 M |
| Extra Money Paid to Buy the New Tubes | $0.68 M |

The extra money paid is much lower than the additional obtained value if they use our new pipes due to the higher corrosion resistance of our new tubes and 20% increase of the thermal power. Therefore, our price is competitive enough to sell in market. In fact, since currently our technology does not face any competitors, we may increase profit until upper limit of benefit margin, determined by bargaining with the customers, comparing the price of new tubes and the value obtained from a new tubes (psychological issues).

## 6.6. Competitiveness of Our Product to Enter the Tubes & Pipes Industry Markets

### 6.6.1. Overview of Porter Analysis

To analyze the competitiveness of our products to enter the pipes and tubes industry market, 5 forces Porter analysis model is used (fig.17). This model is developed by Prof. Michael E. Porter from Harvard to derive 5 forces that determine the competitive intensity and attractiveness of a market. Five forces analysis assumes that there are five important forces that determine competitive powers. These are [51-53]:

(1) Threat of new entry

Power is influenced by the ability of one company to enter a particular market. Factors that can limit the threat of new entrants known as entry barriers are (1) costs in time/money, (2) loyalty to existing major brands, (3) government regulations, (4)high cost of switching company.

(2) Power of Supply

Power is influenced by how easy it is for suppliers to drive up prices. This is driven by (1) number of suppliers, (2) the uniqueness of their products, and (3) the cost of switching from one supplier to another.

(3) Power of buyers

Power is influenced by how easy it is for buyers to drive prices down. This is driven by (1) number of buyers, (2) the important of product for buyers, (3) whether customers are price sensitive, (4) the cost of them to switch from one product/service to another's.

(4) Availability of substitutes

This is affected by the ability of other companies' to find different way of what we are doing. It depends on the uniqueness of our product and how important it would influence one process in an industry.

(5) Competitive Rivalry

This illustrates the intensity of competition among existing competitive industries which depends on (1) the number and capability of our competitors, and (2) the attractiveness of products and services.


Fig.17. Graphical Representation of Porter's Five Forces [51]

6.6.2. Competitiveness of Our Products to Enter the Market

The current metal pipe and tube industry in US mainly engaged in carbon, steel, and stainless steel pipes and tubes manufacturing. Instead of manufacturing the input material (steel, etc) by themselves, they purchased the materials. The major products and services in this industry as shown below:

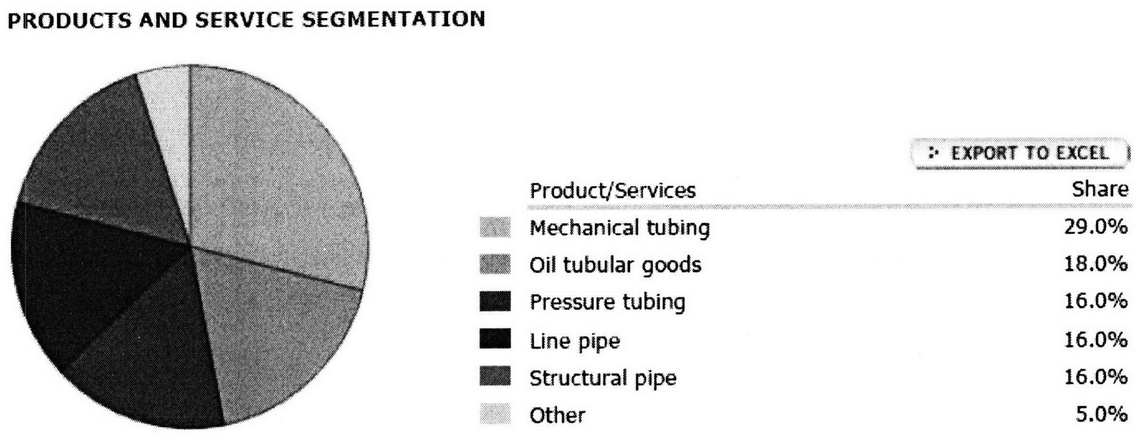


Fig.18. Products Segmentation of Metal Pipe & Tube Manufacturing in the US [54]

As shown in fig.18, the industry's major product is mechanical tubing, 29% of the volume output. Other important products include oil pipe (18%), pressure tubing (16%), line pipe (16%), and structural pipe (16%). Currently there are about 130 enterprises playing in this industry with the four largest ones account for about 42% of industry revenue (fig.19)

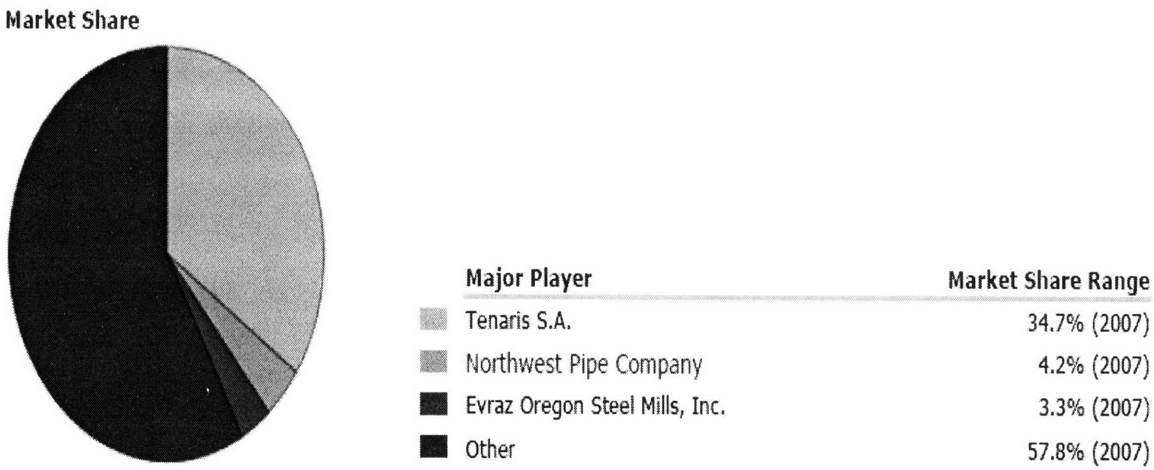


Fig.19. Metal Pipe & Tube Company Major Players in USA [54]

**Tenaris** [54]

It is a steel pipe and tube manufacturer based in Luxembourg with market share 34.7%. Its operation focuses on the manufacturing of tubular steel products used in energy and industrial applications. The major products include production tubing (used to transmit oil and natural gas to the surface), production casing (used to line freshly drilled wells) and surface casing (used during the drilling process). It is the largest producer of oil country tubular goods and line pipe products used in newly drilled oil and gas wells and for transporting oil and gas.

**Northwest Pipe Company** [54]

This company's market share is 4.2% with headquarters in Portland, Oregon. It manufactures steel pipe in three business segments. The first one is to provide large diameter and high-pressure steel pipe products used primarily for water and transmission. The second one is to manufacture half inch to 16 inch diameter, electric resistance welded steel pipe. And the third one is to it falls outside the iron and steel pipe manufacturing industry (propane tanks, pressure vessels, and other fabricated steel products) which accounted for about 5% of company's revenue.

**Evraz Oregon Steels Milss, Inc.**[54]
This company's market share is 3.3%, mainly producing steel pipe, electric-resistance welded (ERW) pipe and structural tubing for plants in Colorado, Oregon, Alberta, and also includes railroad operators, oil and gas pipeline companies, construction companies, and steel products distributor.

From above market share, one interesting conclusion can be taken, most of the large tube and pipe companies do not specialize on producing tubes specified for nuclear industry, or for even more specialized LBE nuclear reactor system. Most of the existing industries tend to focus on the tubes used in oil & gas industries, boiler industries, electric & utility industries, but less on nuclear industries. It is predicted that the concentration of market share and companies producing tubes specified for nuclear companies is more diverse, and not large. To produce one new alloy material for specified nuclear reactors is not easy and need research and development, as well as time and cost. There are no special regulations applied to the Metal and Pipe Manufacturing Industry, although before it starts its operation it should meet local government environmental and zoning requirements like other industries in general. Hence, based on these reasons, it may be said that barriers entry to this industry is medium.

Examining the bargaining power of buyers, our main buyer (LBE nuclear reactor industry) is very important for this technology. This technology is developed to satisfy one of the requirements of highly advanced Gen IV nuclear reactor to be operated in the higher temperature (550°C-700°C). On the other hand, this technology is also important for LBE reactors. Since nuclear industry is large financial funded industry, it should be noted as long as they find technology which can suit their interests, they will pursue their interest, as for this kind industry, the switch cost from one tube supplier to another one is much lower than their nuclear capital and operating cost. Fortunately, our technology is competitive enough as currently this technology is the only one promising one which can satisfy the requirement corrosion resistance and mechanical properties for LBE reactors in the higher temperature. There is no existing IP found for the similar technologies with comparable benefits. Hence, it may be expected that currently the competitive rivalry is not intense. Yet, the R&D should be continued to increase the benefits of this new material since in the future there would be threats of appearing competing technologies. Looking on fig.16 of supply chain, our company buys the T91 material instead of manufacturing it from its elements. It would force our company to rely on the supply of this product. However, it seems T91 has been widely commercialized, so there is likely no strong dependent on a particular supplier of T91. More threatening factor is the price and supply of T91's and our new material's elements (Fe, Cr, Si, Mo). Below is the price metal of each elements required for T91 and our new material fabrication and seems the prices tend to increase in the future (fig.20-23).

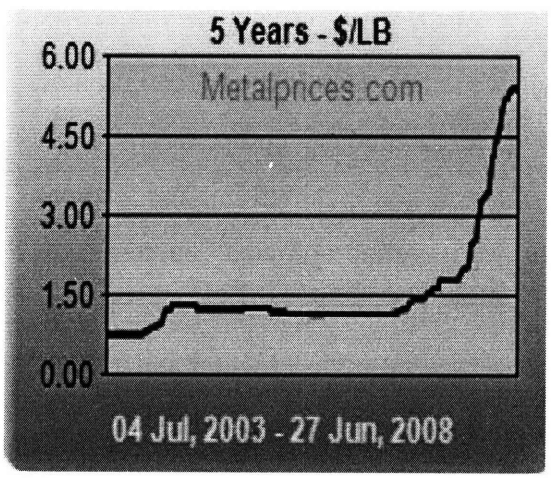


Fig.20. Chrome Price in 5 years [55]


Fig.21. Molybdenum Price in 5 years [55]

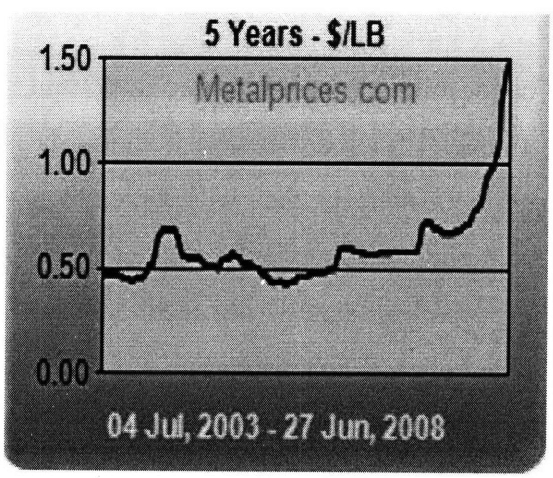


Fig.22. Silicon Price in 5 years [55]

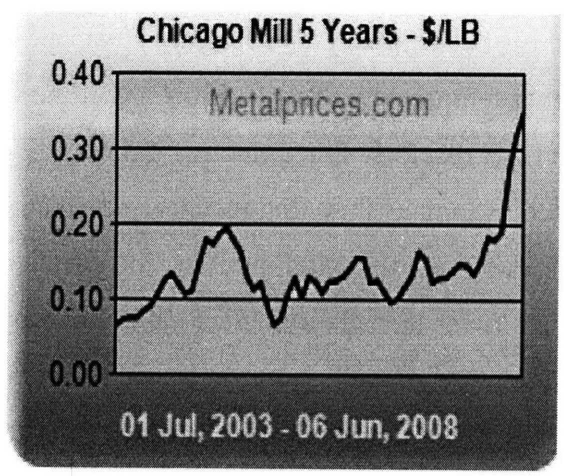


Fig.23. Iron Price in 5 years [55]

In conclusion, with this uniqueness of the technologies for particular nuclear industry, the technology is currently competitive enough to play in the market as summarized in table 15.

Table 15. Potential of Entry and Competitiveness Market of the New Tubes

| | |
|---|---|
| Threat of new entry | (1) Major companies in tubes & pipes industries less focus on nuclear industry<br>(2) Concentration of market share for tubes companies specified for nuclear industry is more diverse<br>(3) To produce new structural cladding material need long R&D, time, & cost<br>(4) No special government regulation to enter the market<br>*****Barrier entry: medium |
| Power of buyers | (1) Manufacturer & Buyer: highly mutual relationship<br>(2) Switch cost from one supplier to another supplier is much less than nuclear capital & operating cost<br>*****The technology is attractive to buyers |
| Power of supplier | (1) Companies depend on T91 suppliers<br>(2) Price of materials elements (Cr, Si, Mo, Fe) tends to increase<br>*****Widely commercialization of T91, less dependency on particular T91 supplier, but more on elements' price |
| Availability of Substitutes | (1) Currently no IP competing technologies<br>(2) Currently there is opportunity to monopolize<br>(3) However, there would be threats from competing technologies in the future<br>*****Continuing R&D needed |

## VII. CONCLUSION AND FUTURE WORK

The functional graded composite of Fe-9%Cr-2.55%Si has potential to be used for Liquid-Bismuth Eutectic (LBE) reactors as structural cladding material. Besides this application, it also can be applied in the chemical and electric utility industry for steam generator applications, heat pipe technology and chemical boilers. Yet, the main customer is still LBE nuclear industry.

In nuclear industry, this Fe-12%Cr-2.55%Si material is then used to fabricate tubes with T91 as the base material. With these tubes, the LBE reactors' temperature is expected to rise up to 550°C-700°C since this cladding material has good corrosion, creep, and mechanical strength while used in such higher temperature and in lead-alloy coolant environment. Furthermore, though these new tubes have higher price with current price of currently used T91 tubes, these tubes are competitive enough by providing comparably additional benefits. Increasing nuclear temperature up to 650°C will provide increase the reactor's thermal power by 20%, and as shown above, the extra money paid by LBE customers is much less than the additional obtained value if using the new tubes. For further commercialization, these tubes are competitive; however, continuing R&D is needed as there would be threats from the other competing material technologies in the future.

For future work, the additional benefit by increasing the nuclear temperature into higher one which is discussed on this thesis is the 20% increase of the thermal power of reactors. Nevertheless, there might be another benefit of the temperature rise, which is the hydrogen production. Exploring this benefit is believed to be able to increase the attractiveness of the new tubes.

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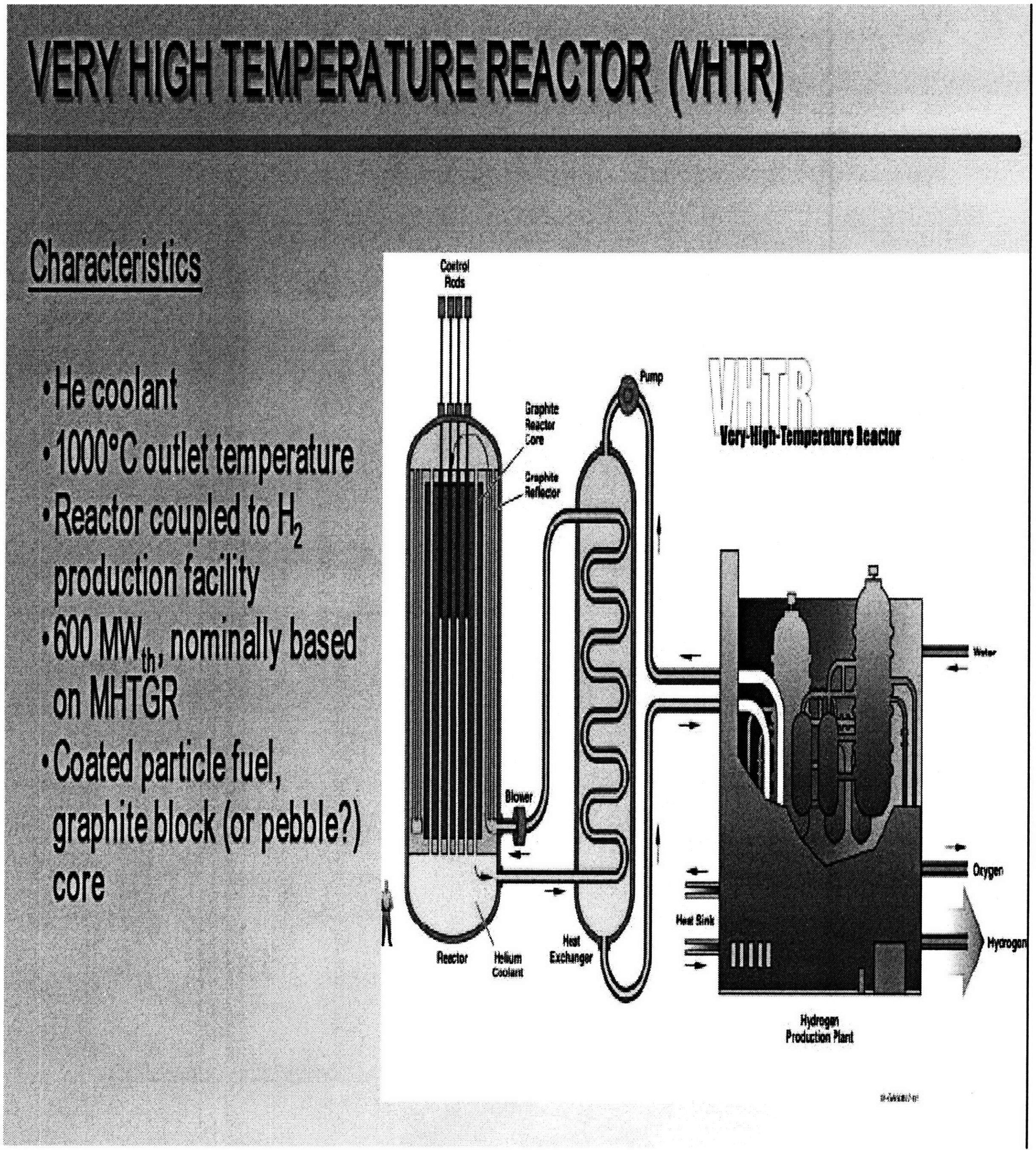
**ACKNOWLEDGEMENT:**

For Academic Discussion & Advice:

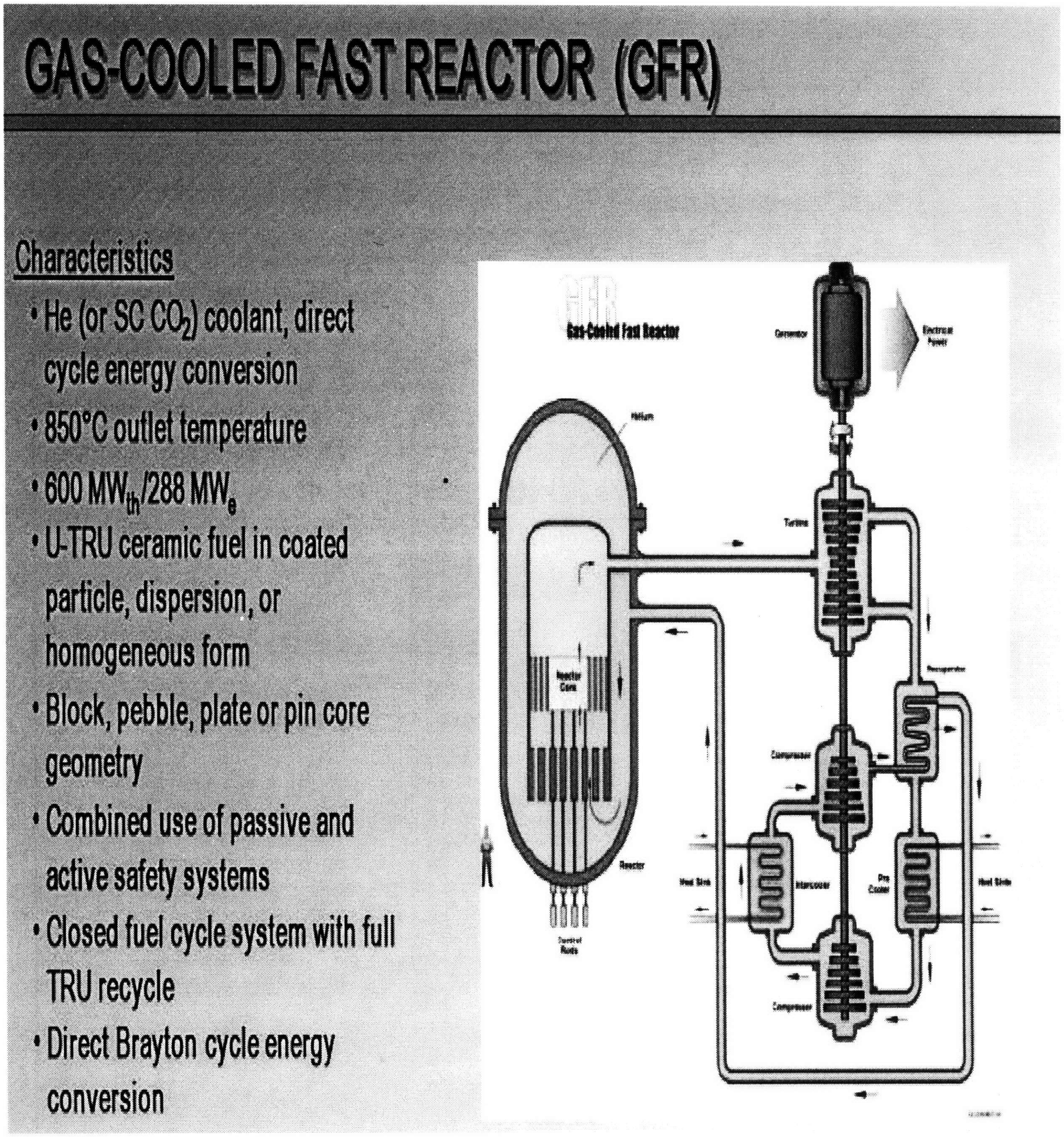
Prof. Ronald G. Ballinger, Mike Short, Henry Liew, Hendra Djaja

Others: My parents, Raga (for jokes during thesis writing), My CHC Church friends (for prayer), SMA fellows

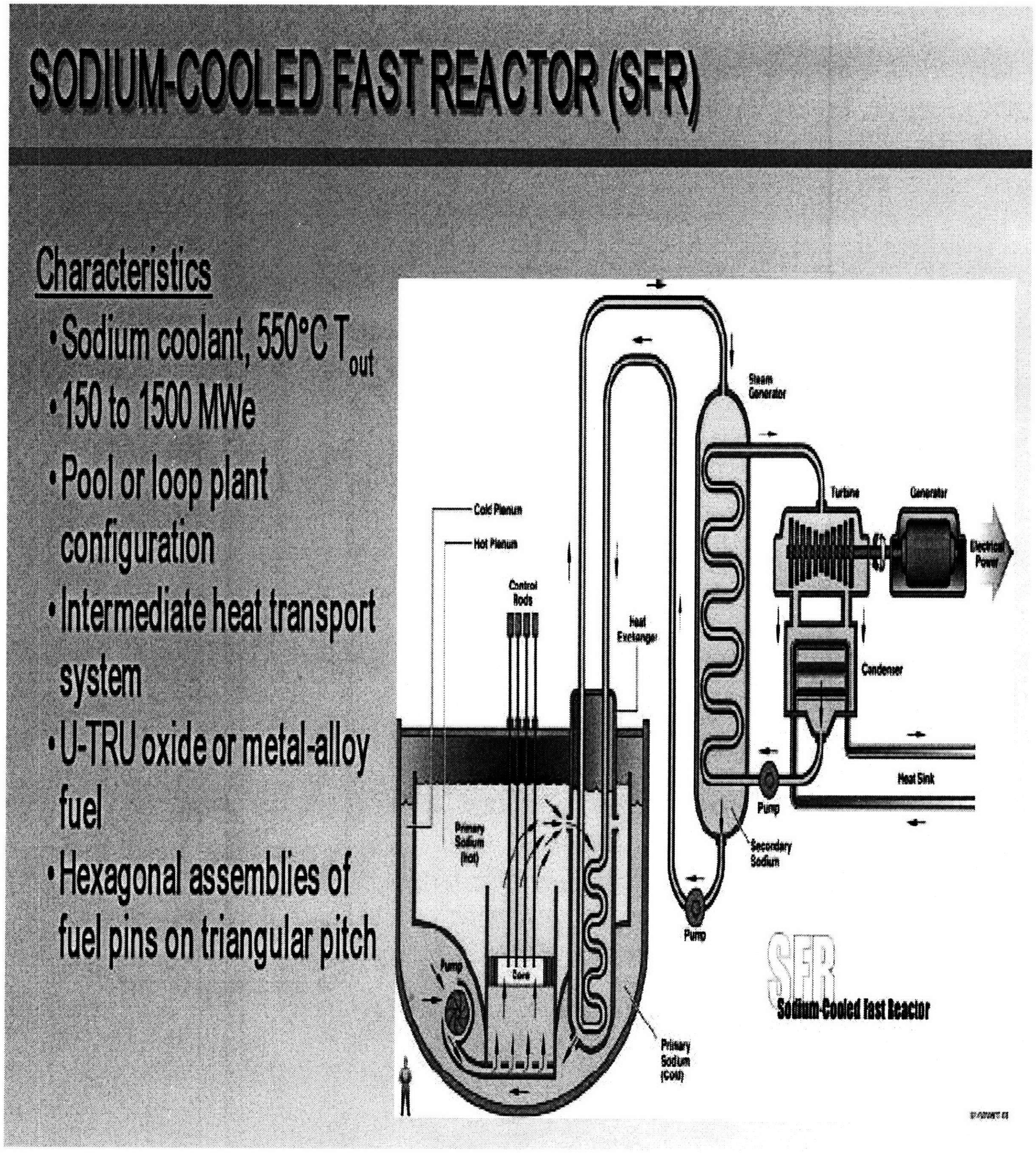
APPENDIX 1: Very High Temperature Reactor (VHTR)



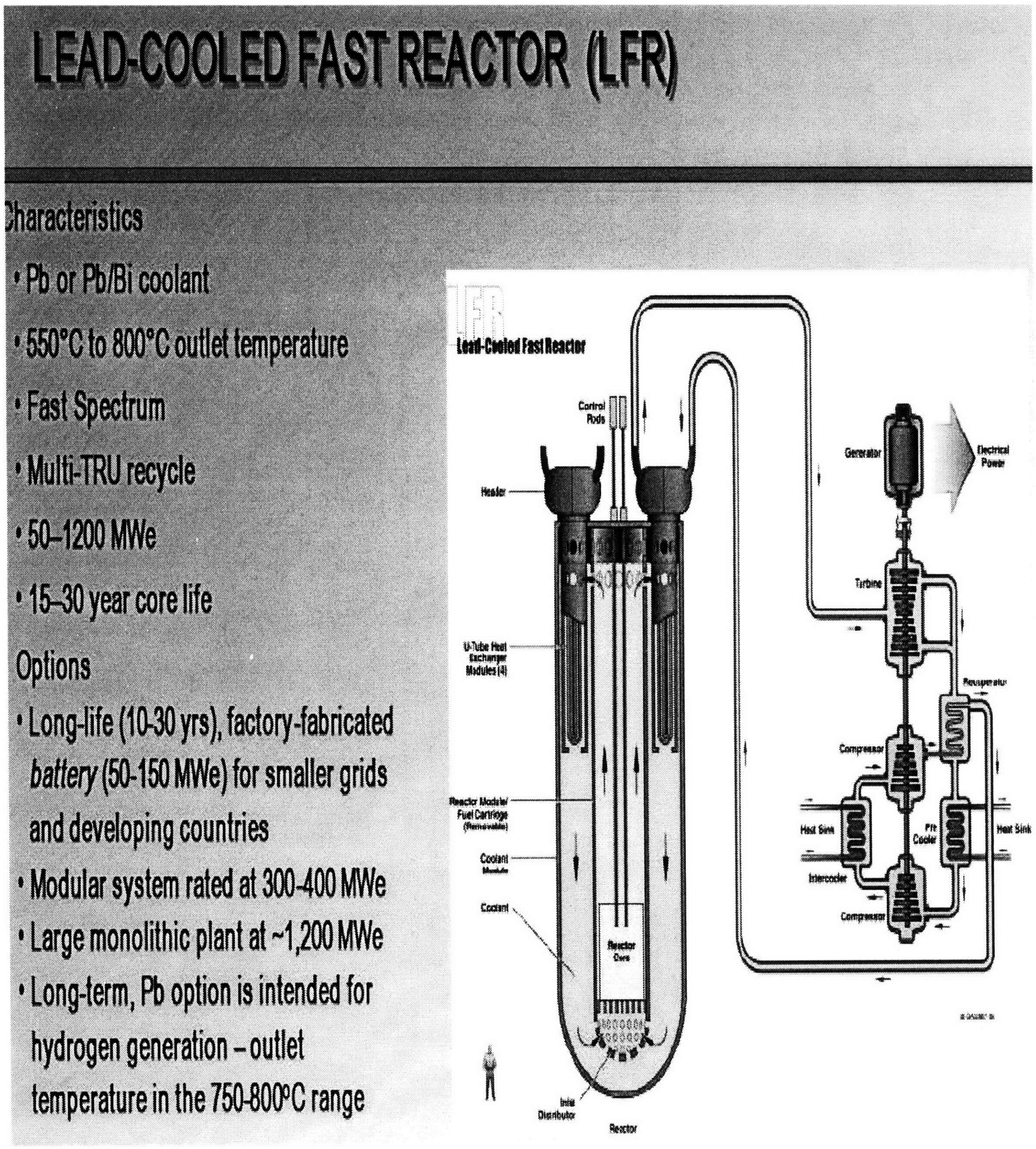
APPENDIX 2: Gas Cooled Fast Reactor (GFR)



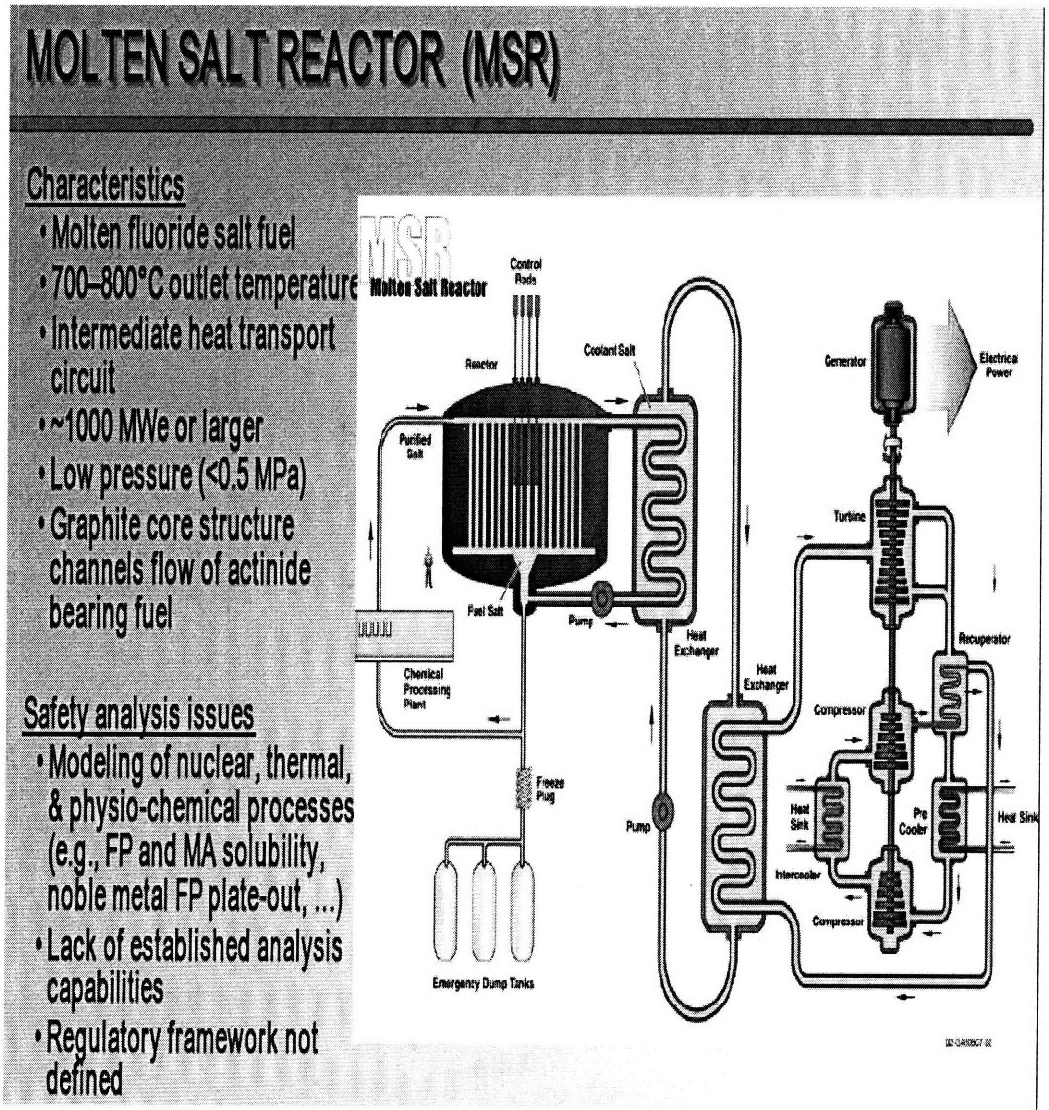
APPENDIX 3: Sodium Cooled Fast Reactor (SFR)



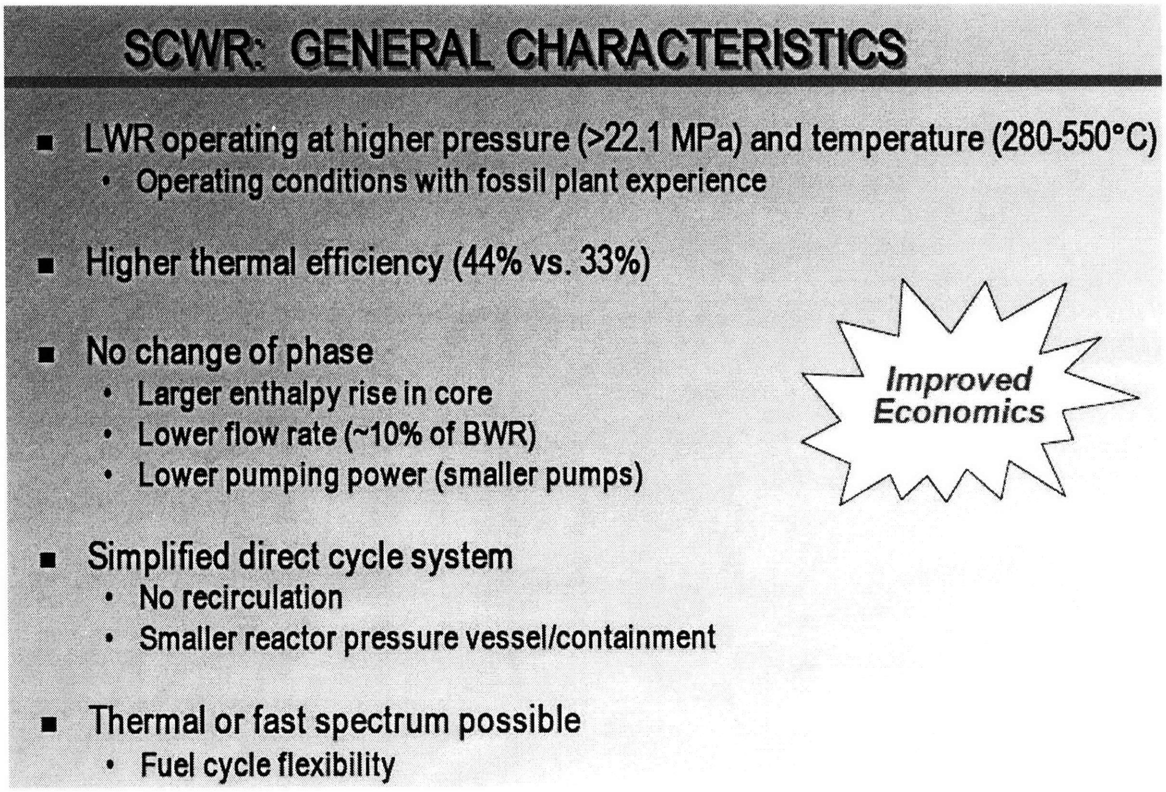
APPENDIX 4: Lead-Cooled Fast Reactor (LFR)

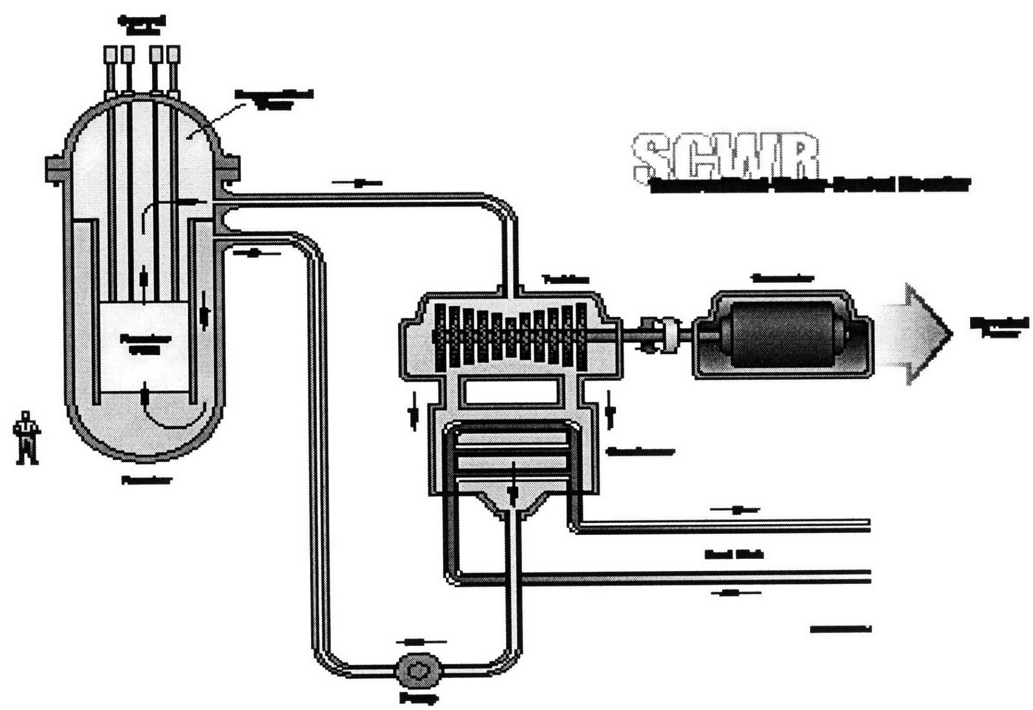


APPENDIX 5: Molten Salt Reactor (MSR)



APPENDIX 6: Super Critical Water Reactor (SCWR)



APPENDIX 7: Calculator of Price Alloy Steel 405

**This free version uses 3 month old data. Subscription required for current prices.**

**Instructions & Help**
**Alloy History**
**Home**

Stainless Steels

405

| Element** | Range % | Calc % | Value $/lb | Last Price | Last Update*^ |
|---|---|---|---|---|---|
| Chrome in HC Ferrochrome | 11.5-14.5 | 12 | 2.300 | 2.200 - 2.400 | Apr 11, 08 |
| Iron in #1 Bundles Chicago | Bal | 84.2 | 0.267 | 0.263 - 0.270 | Apr 09, 08 |
| Manganese in HC Ferromanganese | 1 | 1 | 1.384 | 1.339 - 1.429 | Apr 11, 08 |
| Si Ferro | 1 | 2.55 | 0 | | |
| Aluminum LME | 0.1 - 0.3 | 0.1 | 1.416 | 1.374 | Apr 11, 08 |
| C | 0.08 | 0.08 | 0 | | |
| P | 0.04 | 0.04 | 0 | | |
| S | 0.03 | 0.03 | 0 | | |
| **Total Virgin Value:** | | **100** | **0.5161** | | |
| | | **Scrap %** | 61.59 | **61.59% Jul 11, 08*** | |
| US Dollar | | **Scrap Value:** | **0.3178** | | |
| ◉ lb ○ kg | | Calculate | Reset | History | |

*Indicates Maximum.
**Place cursor on Element Symbol to view detailed description.
*^ LME Prices are updated twice daily with Official and Unofficial (close) prices.
***This value defaults to the daily scrap discount for 304 Stainless (18-8) established by Metalprices.com.

APPENDIX 8: Assumption of Cost Analysis (1)

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | alloy 405 | 30 milli inner cladding | |
| Volume of tube 20-25 feet of 2'OD pipe | | 0.006078 | m3 | | 0.002268 | m3 |
| Density of T91 | | 8.08 | Mg/m3 | | 7750 | kg/m3 |
| Mass of T91 for 1 unit pipe | | 0.049112 | Mg | | 17.57313 | kg |
| | | 98.22307 | lb | | 35.14625 | |
| Price of T91 material/lb | 5 | | | price/lb | 0.5161 | |
| Price of T91 Tube | 491 | | | | 18.13898 | |
| total price | 509 | | | | | |

| | | |
|---|---|---|
| Working Capital | 7.50% | as of revenue |
| Depreciation & Amortization | 36 | years |
| Inflation | 3% | per year |
| **Funding** | | |
| Loan | 508658.5 | |
| Equity | 30% | |
| Loan | 70% | |
| Repayment of principal | 5 | years |
| Interest | 6% | |
| | | |
| WACC | Weight | Cost |
| Equity | 70% | 0.114 |
| Loan | 30% | 0.060 |
| WACC | | 0.098 |

# APPENDIX 9: Assumption of Cost Analysis (2)

| Project Cost | |
|---|---|
| Machine Cost | $436,000.00 |
| Welding machine & etc | $400,000.00 |
| Extrusion machine | $16,000.00 |
| Cold drawing machine | $20,000.00 |
| Land (=500m2)+Land Building Cost(0.5 of Land Cost) | $290,655.00 |
| Maintenance (10% of Land&Building Cost) | $29,065.50 |

| Price of Land | 387.54 | /m2 |
|---|---|---|

| Production Volume | 2000 | per year |
|---|---|---|
| Production Growth from 2009 to 2025 | -3% | per year |
| Production Growth from 2026 to 2046 | 3% | per year |

| Production Cost | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Variable Cost** | **530.80** | **549.17** | **568.14** | **587.71** | **607.91** | **628.77** | **650.30** | **672.52** | **695.47** | **719.16** | **743.62** | **768.88** | **794.97** | **821.90** | **849.71** | **878.44** | **908.10** |
| Material & Fabrication Costs (T91+ New Alloy) | 510.00 | 527.34 | 545.27 | 563.81 | 582.98 | 602.80 | 623.29 | 644.49 | 666.40 | 689.06 | 712.48 | 736.71 | 761.76 | 787.66 | 814.44 | 842.13 | 870.76 |
| Energy Cost | 20.80 | 21.83 | 22.87 | 23.90 | 24.94 | 25.97 | 27.00 | 28.04 | 29.07 | 30.11 | 31.14 | 32.17 | 33.21 | 34.24 | 35.28 | 36.31 | 37.34 |
| **Fixed Cost** | **15.00** | **15.99** | **17.04** | **18.17** | **19.37** | **20.65** | **22.01** | **23.46** | **25.01** | **26.66** | **28.42** | **30.29** | **32.29** | **34.42** | **36.69** | **39.11** | **41.69** |
| Labor Cost | 15.00 | 15.99 | 17.04 | 18.17 | 19.37 | 20.65 | 22.01 | 23.46 | 25.01 | 26.66 | 28.42 | 30.29 | 32.29 | 34.42 | 36.69 | 39.11 | 41.69 |
| **Selling expenses and G&A** | **7.50** | **7.99** | **8.52** | **9.08** | **9.68** | **10.32** | **11.00** | **11.73** | **12.50** | **13.33** | **14.21** | **15.15** | **16.15** | **17.21** | **18.35** | **19.56** | **20.85** |
| Production Cost | **553.30** | **573.16** | **593.70** | **614.96** | **636.97** | **659.74** | **683.31** | **707.72** | **732.98** | **759.15** | **786.25** | **814.32** | **843.40** | **873.53** | **904.75** | **937.11** | **970.65** |

| 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041 | 2042 | 2043 | 2044 | 2045 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **938.74** | **970.39** | **1003.08** | **1036.84** | **1071.72** | **1107.74** | **1144.96** | **1183.41** | **1223.13** | **1264.16** | **1306.56** | **1350.36** | **1395.61** | **1442.37** | **1490.68** | **1540.60** | **1592.18** | **1645.49** | **1700.56** | **1757.48** |
| 900.37 | 930.98 | 962.63 | 995.36 | 1029.20 | 1064.20 | 1100.38 | 1137.79 | 1176.48 | 1216.48 | 1257.84 | 1300.60 | 1344.83 | 1390.55 | 1437.83 | 1486.71 | 1537.26 | 1589.53 | 1643.57 | 1699.45 |
| 38.38 | 39.41 | 40.45 | 41.48 | 42.51 | 43.55 | 44.58 | 45.62 | 46.65 | 47.68 | 48.72 | 49.75 | 50.79 | 51.82 | 52.85 | 53.89 | 54.92 | 55.96 | 56.99 | 58.02 |
| **26.48** | **26.58** | **26.69** | **26.79** | **26.90** | **27.00** | **27.10** | **27.21** | **27.32** | **27.42** | **27.53** | **27.63** | **27.74** | **27.85** | **27.96** | **28.07** | **28.18** | **28.29** | **28.39** | **28.51** |
| 26.48 | 26.58 | 26.69 | 26.79 | 26.90 | 27.00 | 27.10 | 27.21 | 27.32 | 27.42 | 27.53 | 27.63 | 27.74 | 27.85 | 27.96 | 28.07 | 28.18 | 28.29 | 28.39 | 28.51 |
| **13.24** | **13.29** | **13.34** | **13.40** | **13.45** | **13.50** | **13.55** | **13.60** | **13.66** | **13.71** | **13.76** | **13.82** | **13.87** | **13.92** | **13.98** | **14.03** | **14.09** | **14.14** | **14.20** | **14.25** |
| **978.47** | **1010.27** | **1043.11** | **1077.03** | **1112.06** | **1148.24** | **1185.62** | **1224.22** | **1264.10** | **1305.29** | **1347.85** | **1391.81** | **1437.22** | **1484.14** | **1532.62** | **1582.70** | **1634.45** | **1687.91** | **1743.16** | **1800.24** |

# APPENDIX 10: Cost Analysis (1)

| | Unit | year | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Revenue | | | | 1,580,000 | 1,584,708 | 1,589,431 | 1,594,167 | 1,598,918 | 1,603,683 | 1,608,462 | 1,613,255 | 1,618,062 | 1,622,884 | 1,627,720 | 1,632,571 | 1,637,436 | 1,642,316 | 1,647,210 | 1,652,118 | 1,657,042 |
| Sales Volume | Unit | | | 2,000 | 1,940 | 1,882 | 1,825 | 1,771 | 1,717 | 1,666 | 1,616 | 1,567 | 1,520 | 1,475 | 1,431 | 1,388 | 1,346 | 1,306 | 1,267 | 1,229 |
| Selling Price | $/Unit | | | 790 | 817 | 845 | 873 | 903 | 934 | 965 | 998 | 1,032 | 1,067 | 1,104 | 1,141 | 1,180 | 1,220 | 1,262 | 1,304 | 1,349 |
| Production Cost | $/Unit | | | 553 | 573 | 594 | 615 | 637 | 660 | 683 | 708 | 733 | 759 | 786 | 814 | 843 | 874 | 905 | 937 | 971 |
| | | | | | | | | | | | | | | | | | | | | |
| EBITDA | $/Unit | | 0 | 237 | 244 | 251 | 258 | 266 | 274 | 282 | 291 | 299 | 308 | 317 | 327 | 337 | 347 | 357 | 367 | 378 |
| EBITDA | $ | | 0 | 473,400 | 472,781 | 472,198 | 471,644 | 471,115 | 470,603 | 470,104 | 469,612 | 469,121 | 468,625 | 468,120 | 467,601 | 467,061 | 466,496 | 465,900 | 465,269 | 464,597 |
| | | | | | | | | | | | | | | | | | | | | |
| Depreciation & Amortization | $ | | 0 | 22,134 | 22,941 | 23,776 | 24,639 | 25,532 | 26,455 | 27,409 | 28,396 | 29,416 | 30,471 | 31,562 | 32,690 | 33,856 | 35,062 | 36,309 | 37,598 | 38,932 |
| Eearnings Before Tax (EBT) | $ | | (30,520) | 423,798 | 428,476 | 433,162 | 437,849 | 442,531 | 444,148 | 442,695 | 441,216 | 439,704 | 438,154 | 436,559 | 434,911 | 433,205 | 431,434 | 429,591 | 427,670 | 425,665 |
| Tax Rate | % | | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Tax | $ | | 0 | 127,140 | 128,543 | 129,948 | 131,355 | 132,759 | 133,244 | 132,808 | 132,365 | 131,911 | 131,446 | 130,968 | 130,473 | 129,961 | 129,430 | 128,877 | 128,301 | 127,700 |
| Profit after tax | $ | | (30,520) | 296,659 | 299,933 | 303,213 | 306,494 | 309,771 | 310,904 | 309,886 | 308,851 | 307,793 | 306,708 | 305,591 | 304,438 | 303,243 | 302,004 | 300,714 | 299,369 | 297,966 |
| | | | | | | | | | | | | | | | | | | | | |
| Project Cost | $ | | (726,655) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | |
| Research Cost | | | (70,168) | | | | | | | | | | | | | | | | | |
| Maintenance costs | $ | | | (29,066) | (30,054) | (31,076) | (32,132) | (33,225) | (34,354) | (35,522) | (36,730) | (37,979) | (39,270) | (40,605) | (41,986) | (43,413) | (44,890) | (46,416) | (47,994) | (49,626) |
| (Inc) Dec in working capital | $ | | | (118,500) | (353) | (354) | (355) | (356) | (357) | (358) | (359) | (361) | (362) | (363) | (364) | (365) | (366) | (367) | (368) | (369) |
| Tax on EBIT | $ | | 0 | (135,380) | (134,952) | (134,526) | (134,101) | (133,675) | (133,244) | (132,808) | (132,365) | (131,911) | (131,446) | (130,968) | (130,473) | (129,961) | (129,430) | (128,877) | (128,301) | (127,700) |
| Cash flow before financing | $ | | (796,823) | 190,455 | 307,422 | 306,241 | 305,055 | 303,859 | 302,647 | 301,415 | 300,157 | 298,870 | 297,547 | 296,185 | 294,778 | 293,321 | 291,810 | 290,240 | 288,606 | 286,902 |
| Terminal Value | | | | | | | | | | | | | | | | | | | | |
| Cash flow before financing including terminal value | | | (796,823) | 190,455 | 307,422 | 306,241 | 305,055 | 303,859 | 302,647 | 301,415 | 300,157 | 298,870 | 297,547 | 296,185 | 294,778 | 293,321 | 291,810 | 290,240 | 288,606 | 286,902 |
| | | | | | | | | | | | | | | | | | | | | |
| Project financing | $ | | | | | | | | | | | | | | | | | | | |
| Add: Loan drawdown | $ | | 508,659 | | | | | | | | | | | | | | | | | |
| Less: Repayment of principal | $ | | | (101,732) | (101,732) | (101,732) | (101,732) | (101,732) | | | | | | | | | | | | |
| Less: Repayment of interest | $ | | (30,520) | (27,468) | (21,364) | (15,260) | (9,156) | (3,052) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | |
| Add: Tax shield on interest | $ | | 0 | 8,240 | 6,409 | 4,578 | 2,747 | 916 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | | | | | |
| Free Cash flow | $ | | (318,684) | 69,496 | 190,736 | 193,828 | 196,915 | 199,991 | 302,647 | 301,415 | 300,157 | 298,870 | 297,547 | 296,185 | 294,778 | 293,321 | 291,810 | 290,240 | 288,606 | 286,902 |
| | | | | | | | | | | | | | | | | | | | | |
| Outstanding loan | $ | | 508,659 | 406,927 | 305,195 | 203,463 | 101,732 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

APPENDIX 11: Cost Analysis (2)

| 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041 | 2042 | 2043 | 2044 | 2045 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2,789,371 | 2,970,736 | 3,163,893 | 3,369,609 | 3,588,701 | 3,822,039 | 4,070,547 | 4,335,214 | 4,617,090 | 4,917,293 | 5,237,016 | 5,577,527 | 5,940,177 | 6,326,408 | 6,737,751 | 7,175,839 | 7,642,412 | 8,139,322 | 8,668,541 | 9,232,169 |
| 2,000 | 2,060 | 2,122 | 2,185 | 2,251 | 2,319 | 2,388 | 2,460 | 2,534 | 2,610 | 2,688 | 2,768 | 2,852 | 2,937 | 3,025 | 3,116 | 3,209 | 3,306 | 3,405 | 3,507 |
| 1,395 | 1,442 | 1,491 | 1,542 | 1,594 | 1,648 | 1,705 | 1,762 | 1,822 | 1,884 | 1,948 | 2,015 | 2,083 | 2,154 | 2,227 | 2,303 | 2,381 | 2,462 | 2,546 | 2,632 |
| 978 | 1,010 | 1,043 | 1,077 | 1,112 | 1,148 | 1,186 | 1,224 | 1,264 | 1,305 | 1,348 | 1,392 | 1,437 | 1,484 | 1,533 | 1,583 | 1,634 | 1,688 | 1,743 | 1,800 |
| | | | | | | | | | | | | | | | | | | | |
| 416 | 432 | 448 | 465 | 482 | 500 | 519 | 538 | 558 | 579 | 601 | 623 | 646 | 670 | 695 | 720 | 747 | 774 | 803 | 832 |
| 832,438 | 889,585 | 950,623 | 1,015,813 | 1,085,433 | 1,159,779 | 1,239,167 | 1,323,934 | 1,414,441 | 1,511,068 | 1,614,226 | 1,724,349 | 1,841,901 | 1,967,377 | 2,101,304 | 2,244,243 | 2,396,795 | 2,559,597 | 2,733,330 | 2,918,718 |
| | | | | | | | | | | | | | | | | | | | |
| 40,310 | 41,735 | 43,209 | 44,733 | 46,309 | 47,938 | 49,623 | 51,365 | 53,166 | 55,029 | 56,954 | 58,946 | 61,005 | 63,134 | 65,335 | 67,611 | 69,965 | 72,398 | 74,915 | 77,517 |
| 792,128 | 847,850 | 907,414 | 971,080 | 1,039,124 | 1,111,841 | 1,189,544 | 1,272,570 | 1,361,274 | 1,456,040 | 1,557,272 | 1,665,403 | 1,780,896 | 1,904,243 | 2,035,969 | 2,176,632 | 2,326,830 | 2,487,199 | 2,658,415 | 2,841,202 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 237,638 | 254,355 | 272,224 | 291,324 | 311,737 | 333,552 | 356,863 | 381,771 | 408,382 | 436,812 | 467,181 | 499,621 | 534,269 | 571,273 | 610,791 | 652,990 | 698,049 | 746,160 | 797,524 | 852,361 |
| 554,489 | 593,495 | 635,190 | 679,756 | 727,387 | 778,288 | 832,681 | 890,799 | 952,892 | 1,019,228 | 1,090,090 | 1,165,782 | 1,246,627 | 1,332,970 | 1,425,178 | 1,523,642 | 1,628,781 | 1,741,039 | 1,860,890 | 1,988,841 |
| | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | | | | |
| (51,313) | (53,058) | (54,862) | (56,727) | (58,656) | (60,650) | (62,712) | (64,844) | (67,049) | (69,329) | (71,686) | (74,123) | (76,643) | (79,249) | (81,943) | (84,730) | (87,610) | (90,589) | (93,669) | (96,854) |
| (84,925) | (13,602) | (14,487) | (15,429) | (16,432) | (17,500) | (18,638) | (19,850) | (21,141) | (22,515) | (23,979) | (25,538) | (27,199) | (28,967) | (30,851) | (32,857) | (34,993) | (37,268) | (39,691) | (42,272) |
| (237,638) | (254,355) | (272,224) | (291,324) | (311,737) | (333,552) | (356,863) | (381,771) | (408,382) | (436,812) | (467,181) | (499,621) | (534,269) | (571,273) | (610,791) | (652,990) | (698,049) | (746,160) | (797,524) | (852,361) |
| 458,562 | 568,570 | 609,051 | 652,334 | 698,608 | 748,076 | 800,954 | 857,469 | 917,869 | 982,413 | 1,051,380 | 1,125,067 | 1,203,790 | 1,287,887 | 1,377,719 | 1,473,667 | 1,576,143 | 1,685,580 | 1,802,445 | 1,927,232 |
| | | | | | | | | | | | | | | | | | | | |
| 458,562 | 568,570 | 609,051 | 652,334 | 698,608 | 748,076 | 800,954 | 857,469 | 917,869 | 982,413 | 1,051,380 | 1,125,067 | 1,203,790 | 1,287,887 | 1,377,719 | 1,473,667 | 1,576,143 | 1,685,580 | 1,802,445 | 1,927,232 |
| | | | | | | | | | | | | | | | | | | | |
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| 458,562 | 568,570 | 609,051 | 652,334 | 698,608 | 748,076 | 800,954 | 857,469 | 917,869 | 982,413 | 1,051,380 | 1,125,067 | 1,203,790 | 1,287,887 | 1,377,719 | 1,473,667 | 1,576,143 | 1,685,580 | 1,802,445 | 1,927,232 |
| | | | | | | | | | | | | | | | | | | | |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | |
|---|---|---|
| Payback | 2.98 | years |
| NPV | 3,111,923 | $ |

APPENDIX 12: Analysis of Extra Paid Cost and Additional Obtained Value

| | | | |
|---|---|---|---|
| **Obtained Value** | | | |
| Selling Price | 790 | $/unit | |
| Old T-91 Tube | 491 | $/unit | |
| | | | |
| Power Thermal | 1667 | MWth | |
| Efficiency | 42 | % | |
| Cost | **3.49** | cents/W | |
| Capital Cost | 2.03 | cents/W | |
| Operating Cost | 1.46 | cents/W | |
| Revenue of electricity sold | 8.96 | cents/W | |
| thermal power increase(~650°C) | 20 | % | |
| Obtained Value | 7.66E+06 | $ | |
| | | **7.66M** | **$** |
| | | | |
| **Extra Money Paid** | | | |
| # of tubes | 2271 | | |
| Price of tube/unit | 790 | | |
| | 6.79E+05 | | |
| | | **0.68M** | **$** |