

# AMBASSADE DE FRANCE AUX ETATS-UNIS

## MISSION SCIENTIFIQUE ET TECHNOLOGIQUE



Serge Hagège, [serge.hagege@ambafrance-us.org](mailto:serge.hagege@ambafrance-us.org)  
Attaché pour la Science et la Technologie

Washington le 1 juin 2001

### Utilisation de l'Énergie solaire en Sciences des Matériaux

**Prof Jean Murray, Colorado School of Mines, Odeillo**

La France a joué un rôle de pionnier dans le domaine de l'utilisation de l'énergie solaire en Sciences des Matériaux. Les Etats Unis ont depuis quelques années négligé ce secteur de recherche et beaucoup de chercheurs américains qui s'étaient impliqués dans ce domaine se sont retournés vers l'Europe, et la France en particulier. C'est le cas du Professeur Jean Murray, dont le Directeur de thèse déjà, avait des contacts directs avec Odeillo, et qui a décidé de passer une année sabbatique (2000-2001) en France, travaillant sur le thème de la production de métaux purs utilisant un four solaire.

Le Professeur Murray est tout à fait disposée à prolonger ce séjour par un resserrement des liens entre son laboratoire dans le Colorado et l'IMP à Odeillo. Des échanges de stagiaires et postdocs sont prévus pour l'année 2002. En parallèle, une demande pour un programme entre la NSF et le CNRS a été demandé sur ce thème.

Dans le contexte de la crise énergétique que traversent les Etats Unis en ce moment, on devra voir poindre un retour d'intérêt vers les énergies renouvelables, qui sera de plus renforcé par le basculement de majorité au Sénat. Alors, les Etats Unis devront se retourner vers leurs partenaires internationaux pour rattraper le retard qu'ils ont accumulé tant au niveau scientifique que technologique. Ce sujet, qui doit être reconnu par ses aspects de recherche fondamentale, est très en contact avec des préoccupations industrielles. La personnalité du Professeur Jean Murray montre bien, au delà de son intérêt pour la France, une excellence au niveau académique et des contacts avec le milieu industriel américain. L'établissement de liens solides entre nos deux pays peut être vu, en ces termes, comme un investissement sur le futur.

Au vu des bonnes relations de travail qui se sont établies entre ces deux laboratoires, au vu de la qualité et de la quantité des résultats qui ont été obtenus au travers de cette collaboration, je propose que la Mission Scientifique développe une action dans ce sens pour l'année 2002. La formule d'un atelier aurait le mérite d'élargir cette collaboration à d'autres partenaires français et américains.

Serge Hagège

## **SOMMAIRE DE LA NOTE DU PROFESSEUR J. MURRAY**

La partie *background* rappelle l'historique de la collaboration franco-américaine dans le domaine et *le state of the Solar Material Field* est un point à ce jour de la recherche dans ce domaine en France, en Europe et aux USA. La dernière partie traite plus précisément du sujet de recherche du Professeur Jean Murray en collaboration avec l'IMP d'Odeillo. Un CV du professeur Murray conclut cette note.

### ***BACKGROUND***

#### **State of the Solar Materials Field**

- *France*
- *European Union*
- *United States*
- **Further Collaboration**

#### **High-Temperature Solar Processing for Clean Metals Production: Greenhouse Gas Mitigation and Hydrogen Production**

- **Aluminum and Silicon Production**
- **Potential Economic Impacts for Solar Process Heat in Metals Production**
  - 1) *No ongoing energy charges*
  - 2) *Fixed cost of process energy source: less risk*
  - 3) *Possibility of integrating ore and reduction plants*
  - 4) *Reduction in reliance on bauxite*
- **Potential Impact of a Successful Alternative Silicon Process**
- **Production of Solar-grade PV Silicon**
- **Energy Investment**
- **Potential Impact of a Successful Alternative Aluminum Process**
  - 1) *Replacement of electricity consumed for aluminum production*
  - 2) *Drastic reduction of climate-altering gases*

#### **Conclusion**

#### **CV du Professeur J. Murray**



## **BACKGROUND**

Since its beginnings in the 1940's, the French solar research community, originally housed at the Meudon Observatory and later centered at Mont Louis and Odeillo, has emphasized the use of concentrated solar energy as a unique form of process heat for many applications. The two scientists most responsible for the inception of the field and for the construction of the solar furnaces-Marc Foëx and Felix Trombe-were inorganic chemists by training. Their efforts laid the groundwork for the link between solar energy and chemistry and eventually for the production of energy carriers and storage using reversible chemical reactions. I recently assembled a review of the early French research for publication as part of the review of the field for the *Journal of Solar Energy Engineering*<sup>1</sup>.

My thesis advisor, Dr. Edward Fletcher, also an inorganic chemist by training, became intrigued with the use of high-temperature solar process heat in the 1970's, and arranged a Fulbright Fellowship year at the Institute for Materials and Processes-Odeillo (IMP). He returned to his teaching position with experience and practical knowledge of aspects of research using solar furnaces and, most important, contacts with the various French producers of furnace elements. A solar research furnace was subsequently designed and constructed at the University of Minnesota along the lines of the 6 kW furnace at IMP. It had just been completed when I began my graduate studies.

The accomplishments of the early French researchers in the field of solar chemistry have not been as broadly disseminated and acknowledged as they deserve, and although the most important references for my doctoral thesis were authored by researchers here, I first became aware of the true scope and groundbreaking nature of this work during the 1998 SolarPACES conference held in Font Romeu. I tried at that time to organize a Fulbright Fellowship year at the IMP, but my proposed subject was not chosen for an award. The CNRS search for a researcher to fill a two-year position was announced at the 1999 SolarPACES annual meetings in Jerusalem; I applied.

It has been extremely difficult to receive substantial funding directly from the US Department of Energy for research in the field of Solar Chemistry since the mid-90's; funding from the office of solar thermal power was formally terminated, and though other offices such as the Office of Industrial Technology, Hydrogen Energy or general energy research might have funded such work, there were often other requirements such as significant industrial cost-sharing that made funded fundamental research in the field difficult. I found that virtually all of the researchers who had remained active on projects in solar chemistry through the '80's in the US had redirected their research into other areas by the '90's.

I have been able to receive a level of funding sufficient to contribute to the field since 1989, but it has often been achieved in an indirect manner. For example, I used a Career

---

<sup>1</sup> E.A.Fletcher, "Solarthermal Processing: a Review" *Journal of Solar Energy Engineering* **123**, May 2001; pp63-74; first two pages on the early research at IMP from my text.

Advancement Award from the National Science Foundation to fund a year as a Visiting Scientist at the Paul Scherrer Institute in Switzerland, where I worked on a solar process to make various nitrides by carbothermal reduction of the oxides. A small grant from the Honda Foundation enabled me to explore the possibility of producing aluminum by thermal dissociation of aluminum nitride. A direct grant from the Alcoa Foundation allowed me to work for a summer with a student at Minnesota; similarly, More recently, a Visiting Professorship Award (also NSF) at the Colorado School of Mines gave me limited funding for access to the National Renewable Energy Laboratory solar furnace for preliminary work with the alternative aluminum processes.

## State of the Solar Materials Field

### *France*

The French research in the field of materials, which I will define here as the use of solar process heat with the goal of producing a unique material as its end product, continues to be unique and of a far broader nature than work done elsewhere in the world. There has been a substantial amount of research for CNES on materials for space applications. A special issue of the Journal *Entropie*<sup>2</sup> contains diverse articles on materials research at the IMP. Special test chambers have been developed to allow materials characterization under severe conditions which might be experienced by space vehicles reentering the earth or Martian atmospheres; and by thermal and electronic shields designed to withstand the high-flux environment close to the sun. A series of meetings and discussions were convened between researchers at the Jet Propulsion Laboratory in the US and those experienced in the field of research to characterize materials suited for space applications in an attempt to arrange collaborative work, but a successful relationship never emerged.

A substantial amount of research of very high quality has been done at IMP to characterize the performance of reactors designed for fullerene and carbon nanotube production. Highly-concentrated solar energy appears to be an excellent candidate for the high temperature process heat required for this process. Some collaboration was also attempted on this subject between those responsible at IMP and at NREL; interest remains in developing this further.

### *European Union*

Materials research performed by the DLR, Germany and at the Plataforma Solar de Almeria, Spain (PSA) has tended to concentrate on the use of photochemical effects to produce fine chemicals. In addition, research at PSA has used low concentration to detoxify polluted water. Other research teams, such as those working at the Paul Scherrer Institute, are mainly interested in developing the use of concentrated sunlight to store and transport energy. They perform fundamental materials research in order to support reactor design, not as an end in itself.

### *United States*

In the US, as mentioned earlier, sustained funding has been difficult to obtain directly through the office of solar thermal power. I used NSF funding to investigate the feasibility of producing nitrides by carbothermal reduction of the oxides in a solar furnace. More recently, a researcher at the University of Colorado in Boulder obtained a small grant to initiate a research project at the National Renewable Energy Laboratory (NREL) to produce aluminum nitride by a reaction of the elements using solar process heat as the reaction initiation energy. Other projects of brief duration that I am aware of at NREL have been conducted to investigate the use of solar process heat for vermiculite production, and vapor deposition processes using solar energy.

---

<sup>2</sup> *Entropie* **146-147**, Special Issue on Research at High-Temperature conducted at IMP, 1989.

## **Further Collaboration**

I currently have a research grant from the National Science Foundation (NSF) that will support my stay at IMP for an additional two years after the end of the CNRS contract. With this grant, I can also easily support undergraduate students under an initiative at NSF titled "Research Experiences for Undergraduates (REU)". This summer, I will have two undergraduate students from the Colorado School of Mines working with me; I expect to repeat this every year the grant is in effect. We have plans to submit a more-formal collaborative project through the CNRS in cooperation with Colorado School of Mines.

This opportunity to involve American graduate and undergraduate students in research at IMP is one I very much want to develop further. I have worked through the McBride Honors Program at CSM to identify and recruit undergraduate students for a stay at IMP during the summer; this relationship has worked well. I have not yet sought the next level of formal collaboration between NSF and CNRS, but some programs of cooperation between the two organizations already exist. I am quite sure there is no-one who has (yet) worked out a relationship such as the one I wish to explore .

I remain eligible for many grant programs in the US if I can continue to retain an 0.5 FTE "appointment" as a Research Professor at the Colorado School of Mines. One avenue that I believe would be mutually beneficial to explore would be to have a "matching" 0.5 FTE appointment through the CNRS to make my stay in France more feasible from a social benefits standpoint, with the remainder to be my responsibility to find funding and collaborations through US sources. As one of my areas of interest is the use of high-temperature solar energy in emerging processes that might, in future, be used for metals and hydrogen production, while accomplishing the goal of drastically reducing CO2 emissions, there is bilateral interest in my work.

# **High-Temperature Solar Processing for Clean Metals Production: Greenhouse Gas Mitigation and Hydrogen Production**

Research to develop applications for highly-concentrated solar energy in chemical processes has been largely superseded worldwide by the development of its use for electricity generation. But the most efficient solar-thermal plants built to date have achieved less than 20% conversion solar to electricity, and solar photovoltaic cells are rapidly approaching a comparable conversion efficiency at competitive costs. Part of the difficulty lies in the mismatch between the high-temperatures possible with concentrated sunlight, and the limited temperatures at which thermal cycles for electricity generation can accept that energy.

This is not a limitation that applies to a chemical process. Large amounts of highly concentrated solar energy can be introduced efficiently as thermal energy to a variety of chemical processes. When they require elevated temperatures that can only otherwise be reached using electrothermal means, solar process heat becomes even more interesting. This suggests that if our strategy is to design processes with a dual goal of minimizing CO<sub>2</sub> emissions and of reaching the highest thermodynamic efficiency then we need to examine the unique features of solar process heat. Current research in the field of solar chemistry<sup>3</sup> focuses on how the high-quality solar energy incident in sunbelt regions can be stored and transported as chemical energy to less sunny population centers. Because metals are attractive candidates for storage and transport of energy, a considerable expertise has been developed in the field of metal oxide reduction as it relates to energy production. Metals may be used to generate either high-temperature heat via combustion or electricity via fuel cells and batteries. Many metals or reduced metal oxides can also be used to produce hydrogen via a water-splitting reaction; and the hydrogen may be further processed for heat and electricity generation. When carbon in the form of CH<sub>4</sub> is used as part of the metal reduction process, hydrogen mixed with varying amounts of CO is produced directly, and the process thus becomes a combined metal and syngas process. The synthesis gas so-produced could be used to make virtually any organic chemical; liquid transportation fuels such as methanol might be especially desirable. This represents one innovative way to reduce greenhouse gas emission from two concentrated sources.

Developments by researchers in the field of solar chemistry have brought the feasibility of industrial applications of solar process heat even closer to realization. The concentrated beam from a field of heliostats has been redirected to the ground by a naturally-cooled tower-mounted hyperbolic mirror, and can be further concentrated in a secondary concentrator to reach potential concentrations in the 10,000-20,000 range. This would efficiently produce temperatures high enough to economically replace electrothermal process heat. The chief process design challenge for commercial metals production lies in matching the intermittent nature of solar energy to an efficient process or series of processes.

## **Aluminum and Silicon Production**

I believe there are aspects of the current processes used to produce aluminum and silicon that lend themselves to an efficient use of solar process heat. Worldwide, there is a severe tightening of the electricity market, with important economic implications for the metals produced electrothermally. It may never have made much sense from a thermodynamic standpoint to develop highly concentrated solar energy as a means of producing electricity; it makes a good deal of sense to consider its use when high-temperature process heat is the form of energy required.

---

<sup>3</sup> I am currently the Department of Energy's appointed representative to the International Energy Agency for Task II-Solar Chemistry.



## Potential Economic Impacts for Solar Process Heat in Metals Production

### 1) No ongoing energy charges

The supply of solar process heat at high temperatures does not carry the same economic penalties for industry that accrue with all other forms of process heat to high-temperature processes. There is clearly no ongoing energy charge for solar energy usage. The only associated cost might be a small additional initial investment in higher-quality heliostats to better focus the sun to reach high concentrations for higher temperatures.

### 2) Fixed cost of process energy source: less risk

Risk in the metals industry is imposed by changing costs and fear of increasing energy costs. Companies negotiating new plants work hard to obtain very long-term contracts guaranteeing fixed electric costs. Here, the use of solar process heat may have unique advantages. The capital investment in a solar concentrating facility for electricity generation is frequently not competitive with other cheap fuel sources of energy because of the high initial capital cost. When the present value of all the coal required over the lifetime of a coal generating plant is added to the plant capital cost a preliminary comparison for aluminum reduction at high-temperature suggests that the costs of process heat per kWh for a solar plant is slightly less than for an electrothermal process. With the investment in a solar process facility, a company would derive an advantage from knowing that the energy cost for its process would be constant, covered in the amortization of the plant capital costs. If the costs of global warming are assessed to the producers of greenhouse gases, then the solar-based process would reap further benefits for the company.

### 3) Possibility of integrating ore and reduction plants

Much of the ore for aluminum and silicon production is found in the global sunbelt, which has peak areas in Brazil, Southwestern US, Australia and North Africa. Australia, one of the major bauxite producing nations, has vast regions that receive nearly 3000 kWh/m<sup>2</sup>-year.

### 4) Reduction in reliance on bauxite

Historically, the most important cost factors in aluminum production have been electrolysis energy and Bayer-produced alumina. These have accounted for about 40% and 20%, respectively, of the cost of primary aluminum manufacture. Since the estimated cost reductions required to enable any new process to be competitive through lows in the aluminum price cycle need to be on the order of 50% from the current processes, any new process would have to realize significant cost reductions to be competitive. There is no single cost in the current processes that amounts to such a reduction, and thus, a process that both replaces the Bayer process and changes the energy source appears to have the most potential for commercialization.

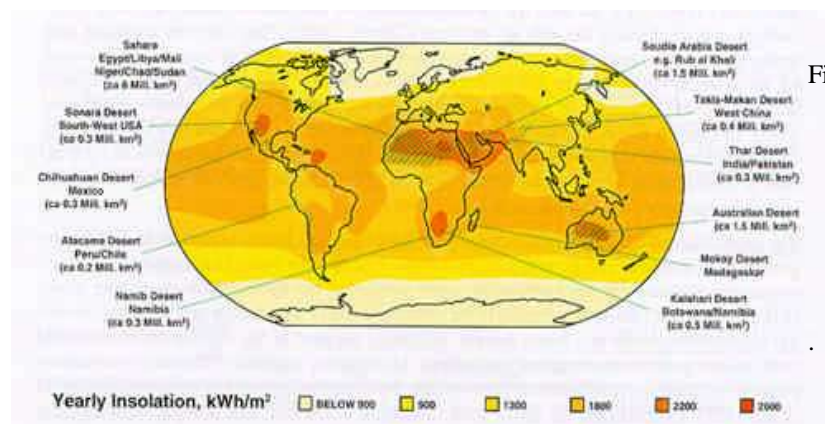


Fig 1. The graphic illustrates areas of peak yearly solar flux, shown in the darkest colors.. Areas of historical bauxite production are the American southeast, western Australia, Jamaica, Brazil and Guinea-all areas that are near the peak solar regions

## Potential Impact of a Successful Alternative Silicon Process

Like aluminum, silicon is difficult to extract from its ore. Unlike aluminum, the reduction of silica with carbon in a thermal process is a well-developed means for the production of metallurgical-grade silicon. The temperature required, over 2000°C, is too high for a conventional combustion-heated blast furnace, and the industrial process uses electric furnace technology. The production of silicon is thus a major source of climate altering gases. Figure 2 shows the energies required for aluminum and silicon reduction by a carbothermal process.

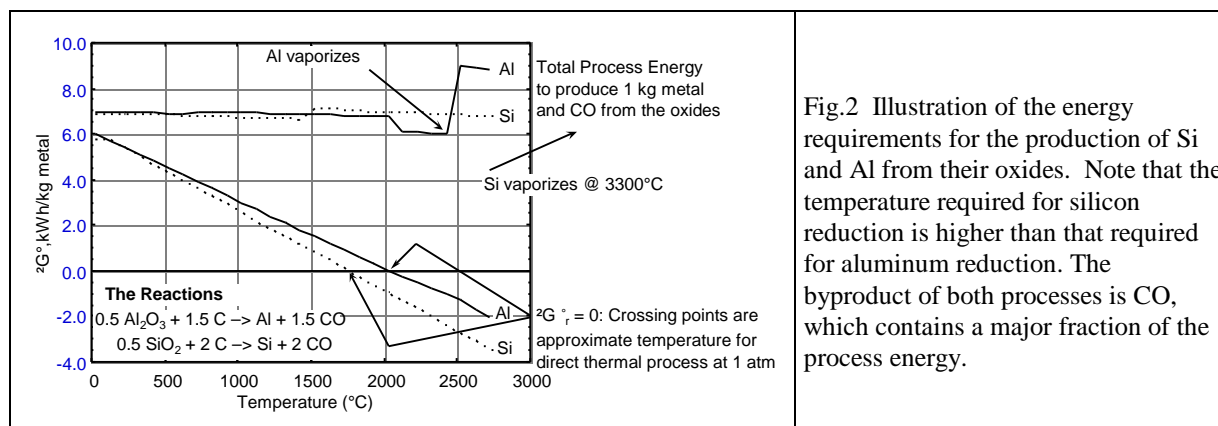
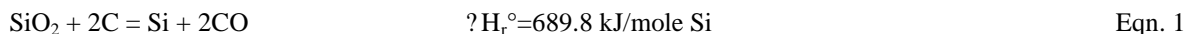


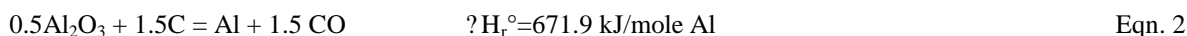
Fig.2 Illustration of the energy requirements for the production of Si and Al from their oxides. Note that the temperature required for silicon reduction is higher than that required for aluminum reduction. The byproduct of both processes is CO, which contains a major fraction of the process energy.

The CO produced in these high-temperature reactions represents an important fraction of the total process energy that must be used to produce the metal. It is thus a valuable byproduct for its energy content, but since it may also be converted to an equal volume of H<sub>2</sub> via the water-gas shift reaction, these metal reduction processes should also be considered to be hydrogen producing processes.

For example, when the reduction reactions are written:



And



then the combustion with oxygen of the CO produced per mole of metal would represent 82% of  $?H_r^\circ$  for reaction 1, and 63% for reaction 2. The industrial process, in its current state of development, consumes about 39 kWh electricity per kg metal produced, and so is comparable to the electrolytic Hall-Héroult process used to produce aluminum.

The production of silicon, if it were accompanied by the water gas shift reaction, would coproduce 2 moles hydrogen per mole Si produced. But the industrial practice is to recover the CO and burn it to provide process heat. In this case, the overall silicon reduction process produces on the order of 14-15 kg CO<sub>2</sub> per kg Si.

## Production of Solar-grade PV Silicon

In electronic chip manufacture, metallurgical grade silicon (MG-Si) of 99% purity or better is reacted with HCl gas to form trichlorosilane (SiHCl<sub>3</sub>), which is further purified by distillation. The SiHCl<sub>3</sub> gas is reduced with hydrogen and deposited on silicon rods. The resulting electronic grade silicon (EG-Si) is 99.99999% Si. The production rate is slow; the process is expensive and extremely energy intensive; and the resulting silicon is more pure than needed by the PV industry. The process is polluting as well, as waste is produced that includes environmentally damaging chlorinated compounds.

Silicon is the most widely used photovoltaic material to convert sunlight into electricity. The current price from the EG-Si process is about \$50/kg, but PV users have a target price less than half of this value, or of about \$6-12/kg. Historically, the PV industry has used the reject and waste silicon material from the semiconductor industry-material that is too impure for IC use but adequate for PV use. This material is variously designated in the literature as solar grade (SG) or PV grade Si, and the purity levels cited range from 99.95% to 99.999% Si. But as the electronic chip manufacturing technology has improved, the efficiency of usage and the scrap rate has fallen and these materials are now either scarce or have become uneconomic for solar cell manufacture. One key need for large-scale implementation of solar electricity is thus low-cost silicon with a sufficient purity for this application. Another, discussed in the Energy Investment section, is to carefully consider the energy demands and CO<sub>2</sub> outputs from the series of processes chosen to manufacture the PV silicon.

Projections by one of the large silicon manufacturers indicate that the PV demand for reject Si will exceed the supply (8,000 metric tons/yr) by a factor of 2 to 4 by the year 2010 (Maurits, 1998). This does not represent a fundamental material shortage problem, because the technology, the quartzite, and the coke needed to make silicon feedstock are in abundant supply. The issue is to supply feedstock with necessary purity at an acceptable cost.

## **Energy Investment**

Besides the inherently large energy required to win silicon from oxygen, the demand for further processing to yield a high-purity material also requires a large energy input. Thus, the time that a PV cell must operate to "pay back" the energy invested in its manufacture is an important measure of the merit of its manufacturing technology. An important study by L.P. Hunt compared the equivalent electrical energy inputs associated with production of EG-Si and MG-Si by various technologies to production of various metals. Results from this study are summarized in fig.3.

When considering the source material from the electronics industry scrap, the exact process used to convert the MG-Si to EG-Si, and the form of the finished product affect the energy investment payback time. The most "economical" combination is about 5 years, and the least economical combination of processes and finished material form has a 20-25 year payback time. This result is directly convertible to the consideration of CO<sub>2</sub> abatement by widespread implementation of solar cells for electricity generation; clearly, if photovoltaic electricity is to be the "clean solar energy" of the future, the choice of technologies used at all steps of the PV module needs to be considered with care, or we may actually increase CO<sub>2</sub> emissions in the short term. The use of solar process heat to replace the initial electric arc furnace process would significantly reduce the CO<sub>2</sub> emissions; but even more interesting, the product gas would be CO which could be converted to H<sub>2</sub> in a subsequent step.

## **Potential Impact of a Successful Alternative Aluminum Process**

### ***1) Replacement of electricity consumed for aluminum production***

Among industries, the primary aluminum industry is a major consumer of electricity. An electrolysis process is currently used for its production, and even after over a century of development, this remains only about 50% efficient. Nearly 10% of the electricity generated globally for industrial purposes is consumed for aluminum production; representing 5% generated for all sectors (OECD, 1983). In 1980, over half of the aluminum industry's electricity came from hydropower, but in the US with increased competition for that electricity source, aluminum smelters in many areas have been shut down, and the portion derived from coal combustion fired plants will increase.

### ***2) Drastic reduction of climate-altering gases***

It is not only the electricity-linked CO<sub>2</sub> resulting from aluminum manufacture that is of concern-the Hall-Héroult electrolytic process uses an electrolyte of composition Na<sub>3</sub>AlF<sub>6</sub> to dissolve the alumina for electrolysis at 960°C. The electric power is provided through carbon electrodes which extend into the molten salts bath, and the carbon in the electrodes also serves to reduce the alumina. Electric power is thus saved at the expense of carbon combustion, with the considerable environmental disadvantage that fluorocarbons are produced. As much as 1.6 kg CF<sub>4</sub> and 0.2 kg

$C_2F_6$  per tonne primary aluminum produced is generated. The residence times of these compounds are estimated to be of the order of 10 millennia, resulting in a global warming equivalent to 15-20 kg  $CO_2$  per kg aluminum. When fossil-fuel electricity is used a further production of about 22 tonnes of  $CO_2$  per tonne aluminum enters the atmosphere, for a potential combined total emission as high as 44 tonnes  $CO_2$  per tonne aluminum (Abrahamson, 1992).

## Conclusion

It is possible to use highly concentrated solar energy as the process heat for carbothermal reduction processes for metals production. Other processes are also feasible, and one particularly promising means of producing Si from its oxide is currently under investigation at IMP. In contrast with process heat from combustion sources, which decreases in quantity as the temperature of end use increases, concentrated solar process heat is available in large quantity at very high temperatures, and is thus an interesting process choice when the goal is to simultaneously minimize energy use and limit  $CO_2$  production. Metals can be produced with a co-production of synthesis gas. With the use of solar process heat, the emission of  $CO_2$  from both these processes would be drastically reduced, and the only  $CO_2$  produced would be directly linked to the stoichiometry of the metal-producing reaction. It is impossible to do better than this when carbon must be used as a reductant for an endothermic process.

For many years, a goal of replacing fossil fuel generated electricity by renewable sources of energy was made at the 10% level. Globally, the production of aluminum consumes about 5% of all electricity generated. The best conversion figures solar-electricity feasible with current technology are in the 20% range, but solar energy can be used with very high efficiency as a thermal energy in a chemical process. Although we have come to accept the use of solar energy for electricity generation, it makes more sense on technical, environmental and economic grounds to investigate and demonstrate the feasibility of using this form of high-temperature energy in chemical processes.

CV, Prof. J. Murray

**JEAN P. MURRAY**

**EDUCATION**

B.S. Mechanical Engineering, University of Minnesota 1977	Graduated with High Distinction
B.S. Physics, University of Minnesota 1977	Graduated with High Distinction
Ph.D. Mechanical Engineering, University of Minnesota 1989 with minors in Public Affairs, Chemical Engineering.	

**PROFESSIONAL EXPERIENCE**

1998-2000	Visiting Professor, Colorado School of Mines Engineering Division, 1.0 FTE
1997	Recipient of Alcoa Foundation Award to support work on High-Temperature Solar Processing for Metals
1992-1993	Guest Scientist with Solar Energy and Process Technology Group, Paul Scherrer Institute, Switzerland.
1989-1997	Assistant Professor Mechanical Engineering, Portland State University, 0.5 FTE
1982-1989	Research Assistant: High-Temperature Solar Furnace
1978-1982	Project Engineer, Industrial Design and Development Rosemount, Inc. Eden Prairie, Minnesota

**UNIVERSITY RESEARCH EXPERIENCE:**

•**Current:** Development of direct reduction of alumina/ore to Al with solar process heat

**PREVIOUS:**

- High-temperature corrosion of ceramic and metallic materials in H<sub>2</sub>S.
- Modelling of gas-phase kinetics: H<sub>2</sub>S and HBr dissociation and quench of products.
- Design & fabrication of fluidized bed reactor/ receiver for steam gasification of cellulose in high-temperature solar furnace.
- Feasibility study of gas-turbine based co-generation system at the Portland International Airport.
- Testing of receiver/reactor system for production of nitrides via carbothermal reduction of oxides using solar process heat
- Review of alternative aluminum processes with goal of identifying well-researched industrial processes most suitable for implementation using solar process heat

**INDUSTRIAL RESEARCH EXPERIENCE**

- Modelling, design, economic justification and installation coordination for a Loss-of-Coolant Accident test facility for Rosemount's products designed for installation in nuclear containment vessels.
- Research in new flowmeter technologies; small diameter Ultrasonic flowmeter and new obstruction-type flowmeter designs.
- Design of the magnetics for new magnetic flowmeter. Work led to award of U.S. Patent 4,459,857 "Electromagnetic Flowmeter" July 17, 1984.

**Ambassade de France aux Etats-Unis - 4101 Reservoir Road, N.W. - Washington, D.C. 20007-2173 – USA**

CV, Prof. J. Murray (suite)

#### RELATED JOURNAL PUBLICATIONS

- “Hydrogen Sulfide as a Source of Hydrogen”, E.A.Fletcher, J.E.Noring and J.P.Murray, *Int. J. Hydrogen Energy* **9**, pp.587-593 (1984).
- “Hydrogen and Sulfur from Hydrogen Sulfide-IV. Quenching the Effluent from a Solar Furnace”, T. Kappauf, J.P. Murray, R. Palumbo, R.B. Diver and E.A. Fletcher, *Energy* **10**, 1119 (1985).
- “Solar Thermal Production of Nitrides by Carbothermal Reduction of Metal Oxides in a Nitrogen Atmosphere”, J.P. Murray and A. Steinfeld, Proc.ASME Int. Solar Energy Conference, San Francisco, USA, pp 59–66, (March 27-30, 1994).
- “Reaction of Steam with Cellulose in a Fluidized Bed Using Concentrated Sunlight”, J.P. Murray and E.A. Fletcher, pp 1083-1098,*Energy-The International Journal.*, **19**,(1994).
- “Metals, Nitrides and Carbides via Solar Carbothermal Reduction of Metal Oxides”, J.P. Murray, A. Steinfeld and E.A. Fletcher, pp695–704, *Energy-The International Journal.*, **20**, 1995.
- “Investigation of Opportunities for High–Temperature Solar Energy in the Aluminum Industry”, final report prepared under Subcontract No. XCK-5-15114 for National Renewable Energy Laboratory, 27 June 1995.
- “Solar-Processed Metals as Clean Energy Carriers and Water-Splitters”; Invited Symposium address at 11th World Hydrogen Energy Conference, Stuttgart, Germany 23-28 June 1996. Proc. Hydrogen Energy Prog.XI. Authors: A. Steinfeld, P.Kuhn, R.Palumbo, J.Murray and Y. Tamaura.; subsequently requested for *Int.J. Hydrogen Energy***23**, pp. 767-774, 1998
- “Aluminum Production Using High-Temperature Solar Process Heat”; J. P. Murray, pp 133-142, *Solar Energy* **66**, 1999.
- “Solar Production of Aluminum by Direct Reduction: Preliminary Results for two Processes”, J.P. Murray, pp125-132, *JSEE* **123**, 2001.

#### Honors and Awards

- Recipient of CNRS Visiting Researcher position at Institute for Materials and Processes, Odeillo
- Appointed by DOE in 1998 to serve as US representative to IEA for Solar PACES task II (Solar Chemistry)
- Invited paper: “Solar-Processed Metals as Clean Energy Carriers and Water-Splitters”; *Int.J. Hydrogen Energy*, **23**, pp. 767-774, 1998. Authors: A. Steinfeld, P. Kuhn, R. Palumbo, J. Murray and Y. Tamaura.
- Alcoa Foundation Award to support continued developments in high-temperature solar thermal processing of metals; 1997
- Invited Symposium address for the 11th World Hydrogen Energy Conference, Stuttgart, Germany 23-28 June 1996.
- Best Paper at ASME International Solar Energy Conference, San Francisco, USA, 1994 for NSF-funded project paper.
- Invited Seminar at National Renewable Energy Laboratory on Nitride Production using High-T Solar Process.
- US Patent 4,459,857 “Electromagnetic Flowmeter” awarded July 17, 1984
- Invited lecture published in Proceedings of the International Workshop on High-Temperature Solar Energy at the Paul Scherrer Institute, August 1995. “Solar Thermal Processes Using Metal Carbides and Nitrides”

Ambassade de France aux Etats-Unis - 4101 Reservoir Road, N.W. - Washington, D.C. 20007-2173 – USA