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A Timely Intervention – Jak Kelly and Solar

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Abstract

This is a personal recollection of my cooperation with Prof. Jak Kelly, who was a friend before he became my father-in-law. Only once did we cooperate scientifically, with an outcome that that we could not have predicted.

Introduction

Jak Kelly and I met in 1977 in the UNSW School of Physics. I was born in Canada, and immigrated into Western Australia after travelling for two years in Africa and Asia. As a graduate student in Physics at WAIT, now Curtin University, I had soon developed an unrefined concentrator concept called the prism concentrator for PV cells (developed three decades later into a ten million dollar start-up in California by people who discovered my work, but that is another story). In 1976, my supervisor suddenly pulled up stakes and departed for Fiji, leaving me without a supervisor experienced in solar energy. After writing to all of the Universities in Australia with solar programs, I joined the UNSW School of Physics as a Master's student under John Guitronich, who had done pioneering experiments with a solar furnace in the 1960s and was trying to set an optical concentration record for parabolic trough concentrators. John kindly agreed to supervise me as a Master's programme even though my area of interest, called "non-imaging optics", was distant from his own.

I began to publish papers in my own little field, with John as co-author, and I soon upgraded to a PhD programme. We received some federal energy research money and populated the solar lab with some bright young researchers. Our lab was opposite the hall from Jak Kelly's office and I found Jak very welcoming and interesting, so I occasionally popped in to chat about the world at large and the microcosm of departmental politics. We had little in common in research terms – he was a materials experimentalist with an emphasis on ion implantation techniques, while I was interested in the limits of geometrical optics. However, my new University programme demanded some course work, so I attended his postgraduate materials science course and found him to be a remarkable teacher.

In 1980, I was invited to Jak's home and met his daughter Karina, a student in English and Archaeology Sydney University. We both graduated in 1980 and were married in 1983. Karina went on to forge a career in TV at SBS, Channel 7 and science broadcasting at the

ABC, and I moved to the University of Sydney Department of Applied Physics, run by Richard Collins under Head of School Harry Messel. Both Karina and Jak were to become Presidents of the Royal Society many years later, with Karina masterminding the move of that Society from Macquarie University to Sydney University and Jak being made a Fellow of the Society late in his life.

An Unwelcome Project

Upon landing in the University of Sydney in 1981, I found myself in a very materials-oriented group, justly famous for developing evacuated solar absorber tubes using spectrally selective coatings under very capable experimental researchers like Brian Window, Jeff Harding, David McKenzie, and the theorist Ross McPhedran. I became interested in using such tubes to develop simple solar collectors with non-tracking mirrors, but enough optical concentration to be capable of producing high temperature steam for electricity generation industrial thermal applications. However, to generate power efficiently, we would need a more efficient absorber coating than had so far been developed.

In 1952, an Israeli researcher Harry Tabor had shown that it was best to design solar absorber surfaces that are highly absorbing (black) in the short wavelength solar spectrum to maximise the absorption of solar energy, and highly reflective ("silvery") in the long wavelength thermal re-radiation spectrum because highly reflective surfaces emit very poorly, so minimal heat is lost (Fig. 1). Tabor designed such a surface called Chrome Black, which was used for many years by the solar water heater industry, but is no longer produced because of environmental concerns about the heavy metal Chromium.

The general view by the early 1980s was that selective coatings were not likely to function well at higher temperatures required for thermal power generation, about 500°C. Jeff referred me to recent papers by D. M. Trotter and A. J. Sievers (1979, 1980). Solar wavelength selective absorber coatings turned out to be a very active topic with hundreds of papers being published every year. For a non-specialist in materials, it was daunting and I had a lot to learn.

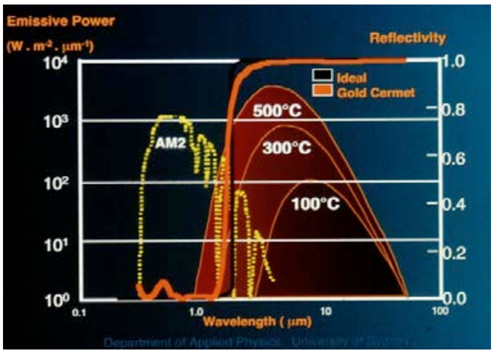


Figure 1: A diagram of the solar selective coating action taken from the author's presentations in the early 1990's. AM2 is the solar radiation spectrum and mountain-like wave forms to the right are spectra for black surfaces at different temperatures. The "ideal" selective absorber surface is shown in black and rises from 0% reflectivity to 100%. The vertical section of the line is called the 'edge'. Complete separation of the solar and re-radiation spectra is impossible, but a near-vertical edge maximises solar collection and minimises thermal loss. Real surface edges produced back in the 1980's were not very vertical and were situated at about 2 microns wavelength.

My department head Richard Collins was of the view that solar systems only had value at low temperatures such as for water heating and perhaps process heat and refrigeration. Having come from a nuclear energy background, he was in favour of nuclear systems for electricity generation.

My ignorance of the materials field caused me to ask questions that others found trivial, but I found some interest from a colleague in the School, Lindsay Botten. I increasingly felt that the conventional 2 micron edge position seemed more like an article of faith than an optimal positioning. In 1983 we published a paper (Mills and Botten, 1983) which suggested that the position and steepness of the edge were critically important to performance. We showed that if we changed the edge position to below 1.8 microns and made it steeper, the ratio of energy absorbed to energy lost could be much improved up to 700°C, well into the realm of high temperature thermal generation. We suggested a surface called the "SIM" and composed of three layers, a semiconductor layer atop an insulating dielectric layer, with a reflector layer at the bottom. The top layer would be more porous going upward so as to better match the refractive index of the air above it and thus reduce reflection losses. The paper noted that "*Selective surfaces of the SIM type would....require concentrations of ~6-7 times at 500°C and ~25 times at 700°C. The former figure can be attained by relatively inexpensive non-tracking adjustable concentrators, while the latter tracking parabolic trough arrays.*"

However, there were no such 'steep edge' surfaces yet available. Two years later I published another paper (Mills, 1985) that refined the theoretical analysis and suggested a possible approach that might be able to use SIM Germanium or Silicon-Germanium cermets (ceramic metal mixtures) as a basis for surface coating with very low emittance. Unfortunately, our Department Head remained strongly opposed to developing high temperature solar energy for electricity production. In a conference paper (Collins, 1986) he wrote that[i]

"*The intrinsic nature of the [renewable] resource make it uncompetitive with fossil fuels in most applications.*"

and

"*Society is unlikely to be dependent on renewable energy in a major way in Australia for many decades, even centuries.*"

It didn't look promising. Clearly, I would not be able to count on Departmental financial or infrastructure support to get this idea to the experimental stage. Fortunately, my non-permanent position continued to be supported by School Head Prof. Harry Messel, who presciently saw value in the work. However, this much appreciated encouragement did not extend to funds for the research. I needed a way to develop the project basics without using departmental resources or even intimating a link to high temperature solar.

The Dad and Dave Grant

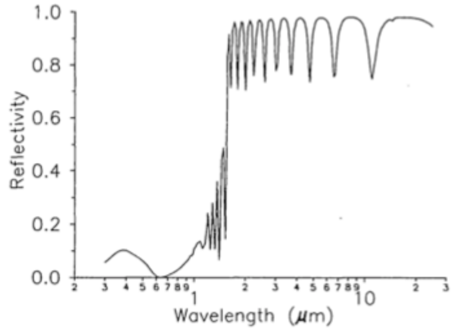
As I had done previously when problems arose at the UNSW, I dropped over to my old department and discussed the situation with Jak Kelly. Quite by chance, I had just come across a paper about ion implantation forming waveguides of germanium oxide in germanium. I asked Jak if ion implantation could be used to allow the production of optical layers of Si/Ge within a dielectric matrix so that information on optical constants might be obtained. He said it could. We began to wonder if there was a workaround for the financial problem. Jak expressed sympathy for my political problems and suggested that we might be able to do some basic experimental work at his UNSW lab in a joint project. We sketched out a joint project with Jak as a lead researcher. It would be a grant for basic optical studies of layers deposited by an ion beam machine. That came under basic science funding rather than energy funding, and incurred no costs in my Department except some of my time. Jak wanted to involve an unusual scholarship student from China called Qi-Chu Zhang. Zhang had survived the Cultural Revolution, was older than I was – about 40 – and had a long background in materials experimentation.

Jak and I jointly applied to the Australian Research Council, and our project, *Ion Implanted Optical Multilayers* received exactly $82,059. Karina was amused by it all and nicknamed it the "Dad and Dave Grant" in homage to the 1930's radio soap opera and later films. We were also successful in a follow-on grant that took the project to 1989. As a first step, the project developed surfaces based on pure Germanium instead of the preferred Si-Ge mixture, and the UNSW part of the team demonstrated very favourable absorptance in the surfaces that was unexpected according to current theory (Zhang, Kelly and Kenny, 1990). By 1989, Jak was approaching retirement and the money was drying up, but by then encouraging lab results provided enough justification for me to apply for NERDDC (energy research) funding, with the research to be carried out back at my base in Applied Physics at Sydney University using sputtering deposition equipment in that department.

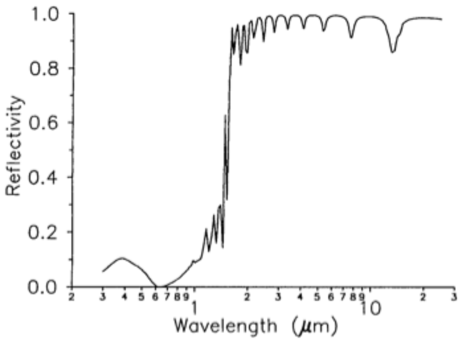
The new grant now clearly emphasized the intention of producing surfaces for a new generation of more efficient and higher temperature solar evacuated tubes. This time there was no opposition; parabolic troughs with chrome black coatings inside evacuated tubes had started to be used in California for thermal operation just above 300°C. Similar systems with more efficient tube coatings should be able to achieve 500°C. The grant application was successful and the project was called High Temperature Solar Evacuated Tube and provided $96,705. I duly hired Zhang immediately after he had successfully completed his doctorate.

The initial emphasis of our project was on developing Germanium-based SIM surfaces using the Sydney University sputtering equipment, and then moving to sputtered Si-Ge surfaces which might yield a better-placed edge position. The first sputtered results were excellent with the deposited surfaces having very low thermal loss by emittance. Fig. 2 shows a comparison of modelled and experimental data from the work. The measured and calculated reflectivity curves were similar for a layered structure of a Ge and GeO_2 mixture on Ge on a Cu substrate shown in Fig. 2(a) and 2(b), and the surface experimental worked optically very well, with an emittance of 0.073 at 500°C, much lower than previous surfaces in the literature. Zhang was able explain the results using experimental optical constants he had measured and theoretical improvements derived in his PhD thesis.

The original SIM surface concept was finally validated, as was Zhang's newer modelling. We were of course, very happy.



(a)



(b)

Figure 2: Modelled (a) and experimental (b) reflectivity spectra of SIM Ge/GeO₂ surfaces on a Cu substrate. Note the very steep edge behaviour. These figures were are from Zhang, Kelly and Mills (1991). The conference paper published in 1991 included Jak's name as a co-author in recognition of his extensive work with Zhang on earlier ion beam samples which was reported.

But science rarely runs exactly to plan; just the act of investigating something in great detail often produces more than you had ever imagined. I had purchased a faster desktop computer for Zhang's modelling and during a delay in the delivery of Ge material, he used his new machine to perform more than 1000 runs using his methodology, allowing optical constants and surface thicknesses to be varied to converge on an optimal optical configuration. It was a brute force calculation that took many days, but the result was a big surprise.

Germanium was very expensive and the SIM layers were relatively thick (about 2 microns), increasing sputtering time greatly. What Zhang showed me were modelled surface performance results that approximately equalled the performance of an SIM surface, but used much thinner layers. Furthermore, the new surfaces did not employ expensive thick semiconductor layers at all. The new layers could be made by co-sputtering common inexpensive metals or dielectrics. The new surfaces were very different; instead of a gradual variation in refractive index in the top layer to promote high solar absorption, as was standard in the field, the new surface used two very thin homogenous cermet layers, each with a different refractive index as illustrated in Fig. 3.

We hadn't finished our Ge work, but we knew this discovery was very important. I applied to NERDDC to change the technical direction of the project and the funders agreed that the new surface should be a better candidate for low cost high volume production.

The new surface was named the "Double Cermet" coating and it was first announced at the Conference of the Australian and New Zealand Solar Energy Society (Zhang Kelly and Mills, 1991), followed by a paper in Applied Physics Letters (Zhang and Mills, 1991a) and later papers (Zhang and Mills, 1991b, 1992 and 1996) as the idea developed.

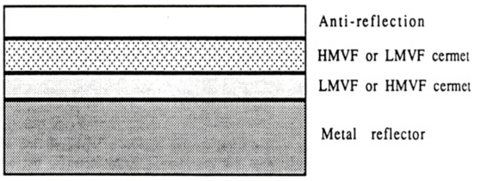


Figure 3: The new film structure was composed entirely of homogeneous layers. From the top downward, a thin anti-reflective coating using a low refractive index material is followed by two cermet layers of differing refractive indices and then a reflective layer underneath. It didn't much matter whether the high metal volume fraction (HMVF) cermet layer was above or below the low metal volume fraction (LMVF) cermet layer; the refractive indices could be adjusted to make them work similarly. It was also found that three cermet layers could improve performance slightly, but would probably not be cost-effective, and four or more gave no improvement. The figure is the original from Zhang and Mills (1990).

Fig. 4 shows calculated and experimental reflectance spectra for a surface using Cu-SiO_2 cermets on a Cu reflector layer. The steepness of the edge in Fig. 4 is apparent; it could be improved further as well, as shown by the gold line in Fig. 1 for a later experimental surface using a gold reflector layer. Many variants of the surface were prepared in the lab and a practical sputtered version using stainless steel carbide cermet became popular for commercial water heating applications.

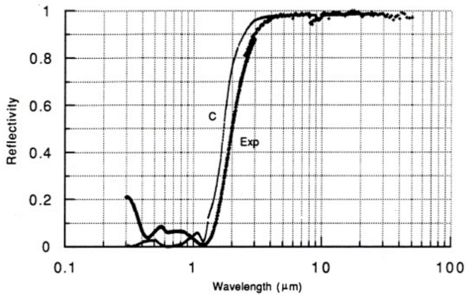


Figure 4: The experimental absorption and emittance of 0.911 and 0.0594 compared quite well with an ideal surface (edge at 1.8 micron) having values of 0.959 and 0.0275, and the double cermet emissivity was lower than the previous Ge/GeO surface value of 0.073. The small absorption reflectivity in the visible shown decreases absorption compared to the ideal of zero, and the experimental surface edge was closer to 2 rather then the desired 1.8, but the results are in reasonable agreement. This figure is from Zhang and Mills (1991).

A Fortunate Intervention

The double cermet surface and other university evacuated tube technology were licensed to the Chinese companies Turbosun in 1996 and Himin in 2004. The technology soon spread to other companies in China. Today, the number of evacuated tubes produced each year in China for hot water is in excess of 100 million, and many premium tubes use the double cermet surface. Well over 100 million people use Sydney University-derived solar hot water systems, which in China had a thermal capacity of 118,000 MW in 2012. A large number are now imported to Australia for water heating as well.

In addition to hot water applications, the double cermet surface coating provided a new inspiration for coatings used in high temperature evacuated tubes for parabolic trough and linear Fresnel systems developed in the last decade, as we had hoped in the 1980s. Parabolic trough collectors now use evacuated tubes with temperatures of operation of 500°C, and even higher temperatures are now being investigated. Their spectrally selective absorber coatings use additional adjacent anti-diffusion layers to preserve the integrity of the basic surface structure at such temperatures, but optically they operate similarly to the 1991 laboratory double cermets. Trough concentrating mirrors provide in excess of 25 times concentration, higher than we suggested in early days, but the commercial surfaces used aren't quite as efficient as the theoretical surfaces that we proposed back in 1983 and 1985 so higher concentration is needed at 500°C Whatever the reflector system, high temperature selective coatings in evacuated tube receivers have become commercial reality. It is extraordinary to think that such a tiny team not only solved the seemingly intractable problem of how to make high highly selective solar absorbers once, but twice.

Looking back, the important decision by Jak Kelly to host development at a critical time in undoubtedly saved the project. Jak was a nuclear fusion advocate in his later years, but his almost limitless enthusiasm embraced many fields. In this solar project, his immense experience in materials science, provided excellent guidance and an ideal experimental platform for his brilliant PhD student, Qi-Chu Zhang. Even though Jak was not directly involved in the later double cermet work, the UNSW-based ion beam effort proved a firm grounding for the Zhang's later computer simulation and experimental work using sputtered surfaces at the University of Sydney.

Zhang later returned to China as the CSO of Himin and oversaw for many years the development of that company's tube coating facility. He is semi-retired and remains a citizen of Australia. His family lives in Sydney.

Jak passed away in 2012, but lived to hear of the impressive commercial results of his timely contribution and was always very chuffed that many millions of people were using this low thermal emissions technology every day.

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