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Where should the national R&D in materials science fit into South Africa's future nuclear power programme?

by W.E. Stumpf*

Synopsis

South Africa recently announced a resurgence in its commercial nuclear power programme. The implications for the development of the necessary high-level manpower within South Africa's tertiary educational system and its national research and development (R&D) capacity in materials science and engineering, as well as in other engineering disciplines, are placed into perspective. An organized national process of developing this manpower by moving away from the previously high-risk and costly 'large programmes' to rather a selection of 'small and better' research projects and a redefinition of what constitutes 'nuclear materials' are proposed as parts of this strategy.

Keywords

materials science, pressurised water reactor, zirconium based cladding materials, uranium enrichment, steam generator.

Introduction

Since 2008, and more particularly in 2014/2015, South Africa has woken up to the fact that significant steps need to be taken to ensure sufficient electricity generating capacity for the future, even beyond the coal-fired stations at Medupi and Kusile currently under construction. It is, therefore, encouraging to see some active large-scale wind farms in the Eastern Cape near Jeffrey's Bay, in the Couga area, and others in the Western Cape already in operation. In addition, many solar energy projects are also progressing from the small localized scale to larger programmes in the Northern Cape, which may contribute some capacity on a national basis. South Africa needs to tap into its renewable resources of wind and solar much more, but will these projects solve the country's long-term industrial needs? Unfortunately not. One cannot run mines and trains on solar cells. Industry needs reliable baseload capacity, and with very limited easily accessible hydro-capacity this leaves really only coal, possibly natural gas, and nuclear power as options. South Africa's current over-reliance of about 90% on coal–fired power, however, places it in an internationally vulnerable position, and diversification into a more equitable energy mix should be a national priority for the medium to long term. South Africa cannot simply ignore the mounting evidence of significant climate change confronting the human race, as the IPCC cautioned in 2013, and will have to adjust its future energy reliance to a more balanced combination of sources.

After many years of international conferences, meetings, and working group sessions, the world is no nearer to finding an equitable and binding international agreement on measures to curb climate change. It is, therefore, highly unlikely that the more acceptable low-emission scenarios such as the RCP2.6 (Figure 1) are realistic, and current trends appear to indicate that the world is facing a more pessimistic climate change future, such as the RCP8.5 scenario.

Does this mean that South Africa will need to completely phase out coal-fired power in the medium to long term? No, that would be impossible, and even irresponsible, but it does mean that a future energy mix of about 50% coal-fired, 25% nuclear-based, and 10% imported gas-fired power, with the remaining 15% consisting of renewable energy sources, would be a typical future to plan for. Such a scenario would constitute a baseload capacity of about 80–85% with the remainder comprising renewable energy sources, mainly wind and solar.

Such a turnaround from a very high to a more reasonable dependence on coal plus a still limited nuclear dependence will place heavy demands on South Africa's technical expertise to select, evaluate, and later to supply the materials that are 'fit for purpose' in the planned nuclear power programme.

Broad classification of nuclear materials in a pressurized water reactor

Although a modern nuclear power reactor such as a pressurized water reactor (PWR) consists

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in essence of the same main components as those for a coal-fired plant, *i.e.* a heat source, a steam generating system, and a steam-driven turbine/generator combination, the operating and safety requirements make a typical PWR a far more complex system that requires specialized materials. Figure 2 shows a broad overview of the typical materials currently in use in a modern PWR. Note the wide range, from low-alloy steel to more sophisticated ferrous and stainless steel alloys, from nickel-based creep-resistant alloys to corrosion-resistant titanium condenser tubes, from zirconium-based

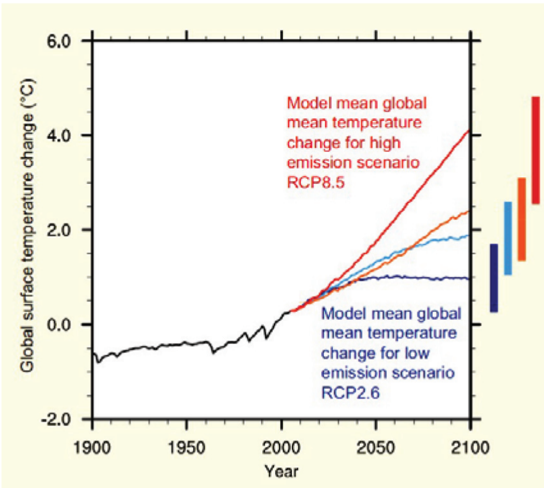

Figure 1 – Estimated IPCC global surface temperature changes for various models of climate control through curbing CO_2 emissions (IPCC, 2013)

fuel cladding to boron-based control rod materials, from electrically conductive copper to cathodically protected tube sheet and, last but not least, oxide fuel pellets. Production and manufacturing processes for these materials range from cast components to wrought and welded tubes and sheet, from passivated surfaces to corrosion-resistant weld-cladding, from sophisticated to more conventional heat treatments, from high purity to standard material purities, from solid to porous sintered items, and so on.

Such a wide range of materials of construction poses a tremendous challenge to South Africa's materials engineers and scientists if they wish to grow into and actively participate in an expanding nuclear power programme. To simply sit back while all of the know-how is imported, even in the long term, is not an option. On the other hand, to consider actively mastering the know-how for all of the above materials is also unrealistic. Some hard choices, therefore, need to be taken to rather focus on those areas where maximum benefit can be gained within the limited research resources at the country's disposal.

The need for materials science in PWR technology

In assessing the broad research focus areas of South Africa's science, engineering, and technology (SET) sector in preparation for a future resurgence of nuclear power, one needs to firstly recognize the somewhat onerous process of development, testing, evaluation, and safety assessment before adoption, as described so elegantly by Hoeffelner (2011) (Figure 3).

The entire cycle of materials development, from conceptual definition until final introduction in practice, can in essence be separated into two main focus areas: firstly, the

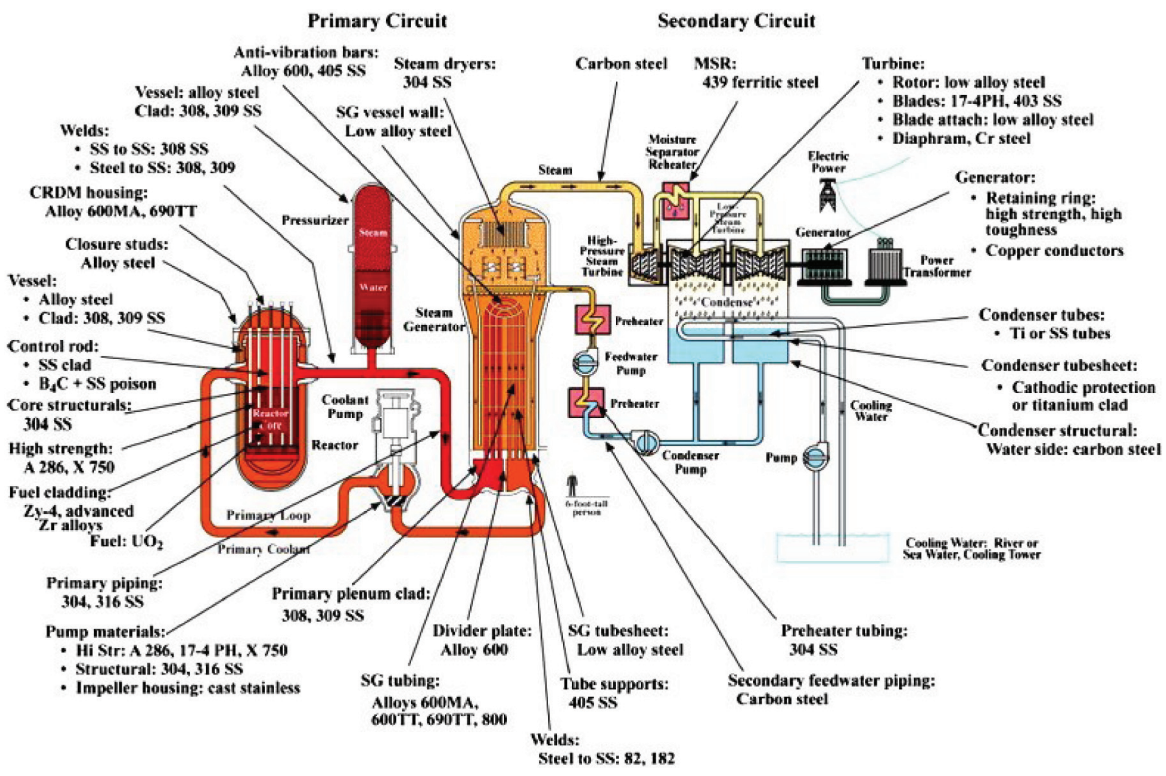

Figure 2 – Typical structural materials in use in a modern PWR (Zinkle and Was, 2013)

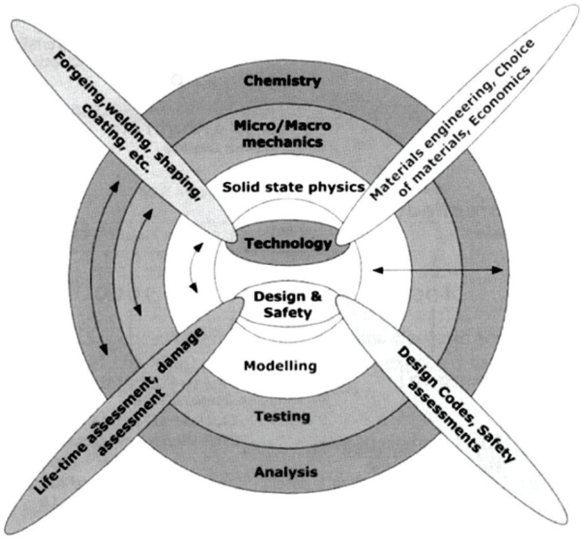

Figure 3 – The process of new materials development, testing and evaluation, design, and safety assessment in nuclear materials before acceptance and introduction (Hoeffelner, 2011)

upper issues of technology, and secondly, the lower issues of *design and safety assessment*. The two focus areas go hand-in-hand, and South Africa's endeavours in nuclear technology over the past three or four decades have taught some hard lessons of the consequences of focusing primarily only on the development of the technology, without planning for the resources to bring the technology into safe, reliable, and cost-effective commercial fruition, which placed the entire process at risk of termination. This was a classic *technology push* instead of a *technology pull* approach.

The demands of the entire development cycle as depicted in Figure 3 can partly be recognized in the unfortunate terminations of the uranium enrichment programmes (both the Vortex and the Molecular Laser Isotope Separation (MLIS) systems) and the development of high-temperature gas-cooled reactor technology in the pebble bed modular reactor (PBMR) programme. In all of these programmes the technology developed by South Africa's scientists and engineers was on an equal level with international norms, leading even to international participation in the MLIS program. During a visit in the early 1990s to the Vortex uranium enrichment Z-plant for low-level enrichment, a group of international engineers from a leading country in the area of enrichment just shook their heads and commented: 'we would never have been able to design and build such a plant'.

Why, then, did all three of these programmes falter in the end? The exact reasons are, of course, different in each case, but overall all three really faltered due to one common factor: the lack of sustainability of resources needed to take each one through the entire life-cycle of development shown in Figure 3, and then into full commercial viability. It was as simple as that! South Africa must recognize that it is a relatively small country with very limited resources, and furthermore, new technology always carries a high risk of failure even if the R&D is on a par with international norms.

The crucial question regarding South Africa's future nuclear power programme, is therefore a fundamental one:

> 'Should South Africa's materials scientists and engineers attempt to be technology leaders as in the past, or should we rather aim to be *technology followers*, but in the process improve on an incremental basis what others have already done, *i.e.* a '*small and better*' focus?

The answer to this basic question can be sought *inter alia* in the path taken by Japan after the end of the Second World War, when a shattered country with limited own resources had to 'climb out of its ashes' by emulating what others had done, but doing it incrementally better. Within a decade or two, Japan had become internationally renowned for its high-quality cameras, binoculars, television sets, and many other electronic and engineering goods.

There is a lesson to be learnt here. South Africa should avoid '*large and new*' high-risk technology programmes and focus rather on the '*small and better*' technical areas that will incrementally draw South African R&D, together with local industry, into growing participation in the future nuclear power programme.

A second strong argument for '*small and better*' lies in the inherent safety and performance guarantees that have to be provided by the reactor vendor. Local participation in the supply of key components, particularly those associated directly with the so-called 'nuclear island', will most likely be very limited for many years to come, at least until South Africa's industrial base has reached a level of sophistication equal to those of the reactor vendor countries. Does this, therefore, mean that no local R&D resources should be focused on these materials? No, not at all!

For purposes of design evaluation, operational optimization, and safety evaluation as depicted in the lower half of Figure 3, decision-makers need to have a clear understanding of the limits of structural materials and a feeling for the behaviour of these materials under severe operational conditions, which often requires much more than 'literature knowledge'. This route will be called '*understanding better*'.

In designing a roadmap for South Africa's materials R&D capacity in the future nuclear power programme, one can therefore once more return to the model of Hoeffelner in Figure 3 and identify two main areas that need to be addressed:

- ➤ Research aimed at the incremental development or improvement of the upstream technology of materials aimed at future supply into a growing nuclear power generating capacity, *i.e.* the '*small and better*' route
- ➤ Developing an understanding of the positive and negative limits of those materials for design, life assessment, and safety evaluation purposes, *i.e.* the '*understanding better*' route.

Each of these will be explored in some detail, with specific examples from the nuclear industry.

Research focus area: technology of nuclear materials

Zirconium-based cladding materials

A very visible illustration of the resources required for a '*large and new*' programme is provided by the development of improved zirconium-based cladding materials for PWR technology.

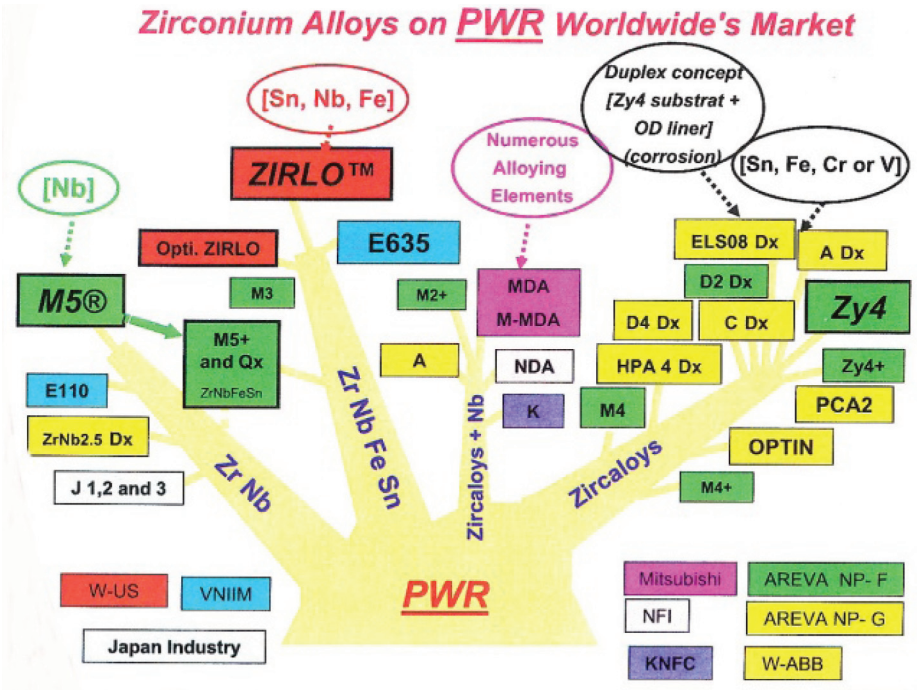

Figure 4 – The development of potential advanced zirconium-based cladding materials (CEA-INSTN, 2008)

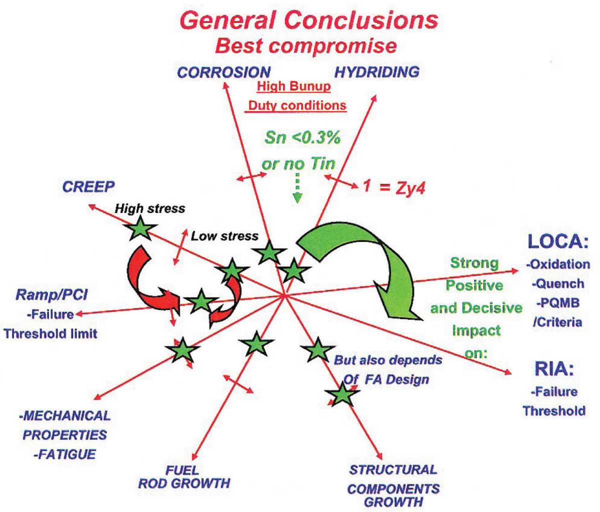

Figure 5 – Technical challenges to be addressed in the development of any advanced zirconium-based cladding materials (CEA-INSTN, 2008)

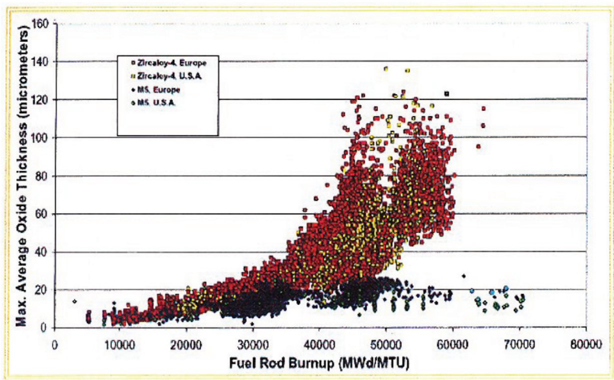

Figure 6 – In-reactor oxide thickness measurements of Zircaloy-4 (red and yellow data points) and the new Zr-Nb alloy M5 (bottom black and green data points) (CEA-INSTN, 2008)

Firstly, where would one have to focus in selecting a new development area? The leading nuclear countries of the world are committing very substantial human and research resources to the development of new alloys.

The difficulty in choosing a new alloy towards which South Africa could make a meaningful contribution is immediately apparent. The development of any new alloy involves a wide range of difficult technological challenges, which often require a compromise in final properties. There is therefore an inherent risk in any choice of R&D on advanced cladding materials.

Finally, the new alloy needs to be proven by means of numerous costly and lengthy in-reactor tests to evaluate its safety performance.

Considering all of the above, it is therefore quite clear that for South Africa to embark on such a '*large and new*' programme of cladding alloy development would be illogical, particularly since a country such as France has seemingly more than 100 engineers and scientists working on such a programme alone. Does this mean that South Africa should withdraw completely from any zirconium-based research? The answer is, clearly, 'no!'

South Africa, together with Australia, supplies most of the world's zirconium-based minerals, and herein lies a particular opportunity in the '*small and better*' route. The current three major processes followed by companies in the USA, India, and France all start off with zircon ($ZrO_2.SiO_2$), which always contains small amounts of hafnium (Hf) substituted for Zr, and use various refining processes to arrive at $ZrCl_4$ followed by reduction to hafnium-free zirconium metal in the magnesium-based Kroll process. All three processes are batch operations, and all of them have environmental and safety implications.

South Africa has the zirconium-based mineral resources, and is recognized internationally for its pyrometallurgical process technology.

Here is a prime example of a '*small and better*' strategy to 're-invent' the whole, or only the upstream steps, of the current zirconium production routes with better technology.

The incremental improvement in the three somewhat similar production routes for nuclear-grade zirconium certainly falls within the capabilities of South African scientists and engineers, and can benefit both the country and the world's nuclear industry in the long term. Necsa, with its internationally competitive capability in fluorine and high-temperature plasma technology, is uniquely placed to accept such a challenge.

Uranium enrichment

In any discussion of South Africa's future nuclear programme, the question of uranium enrichment will inevitably arise. Should South Africa once more embark on such a '*large and new*' venture for its future nuclear programme? This question is probably somewhat easier to answer today than some decades ago. This is due to the following reasons.

- ➤ South Africa's uranium resources are found primarily in gold-bearing ores. When South Africa was one of the world's major gold producers, it simply made sense to also beneficiate the uranium to so-called 'yellowcake' as a by-product. South Africa has since lost its place in the ranking of the top few gold producers. Furthermore, the fall in the price of yellowcake has made it quite uneconomical to extract the uranium from the gold recovery processes. South Africa currently (2013) accounts for only 0.9% of world uranium production (World Nuclear Association, 2013), and is superseded by African countries such as Niger (7.6%), Namibia (7.3%), and even Malawi (1.9%). Because of this unfortunate co-existence of gold and uranium, South Africa had only 5.5% of the world's 'Reasonably Assured Reserves' (RAR, *i.e.* recoverable at a cost of less than US$130 per kilogram U), in 2009 (TradeTech, 2010), a decline from 6.5% of historical production up to 2008
- ➤ Countries to the north of South Africa, however, do produce uranium as a primary product and these countries contain some noteworthy reserves. Could South Africa serve as a regional uranium enrichment centre for Africa? A select working group that was tasked by the Director-General of the IAEA in Vienna in 2007, and of which the author was a member, defined the boundaries of such regional nuclear fuel centres with one of the main criteria being '*majority multinational control*' from outside the region, most likely with the participation of one or more of the five permanent members of the UN Security Council. To bring such a possibility into fruition, however, is fraught with a number of difficult questions, both politically and technically:
  - Politically, nuclear non-proliferation and uranium enrichment will always be very sensitive topics. This is not made easier by concerns about the real intentions of Iran and North Korea (both signatories of the Non-Proliferation Treaty or NPT) and those still outside the NPT, notably India, Pakistan, and Israel. With memories of the Cold War in the previous century still fresh in people's minds and the current instabilities in many parts of the world, it is to be expected that the five permanent members of the UN Security Council, the so-called 'haves of nuclear weapons' within the NPT, would strongly resist any measures to spread uranium enrichment technology.

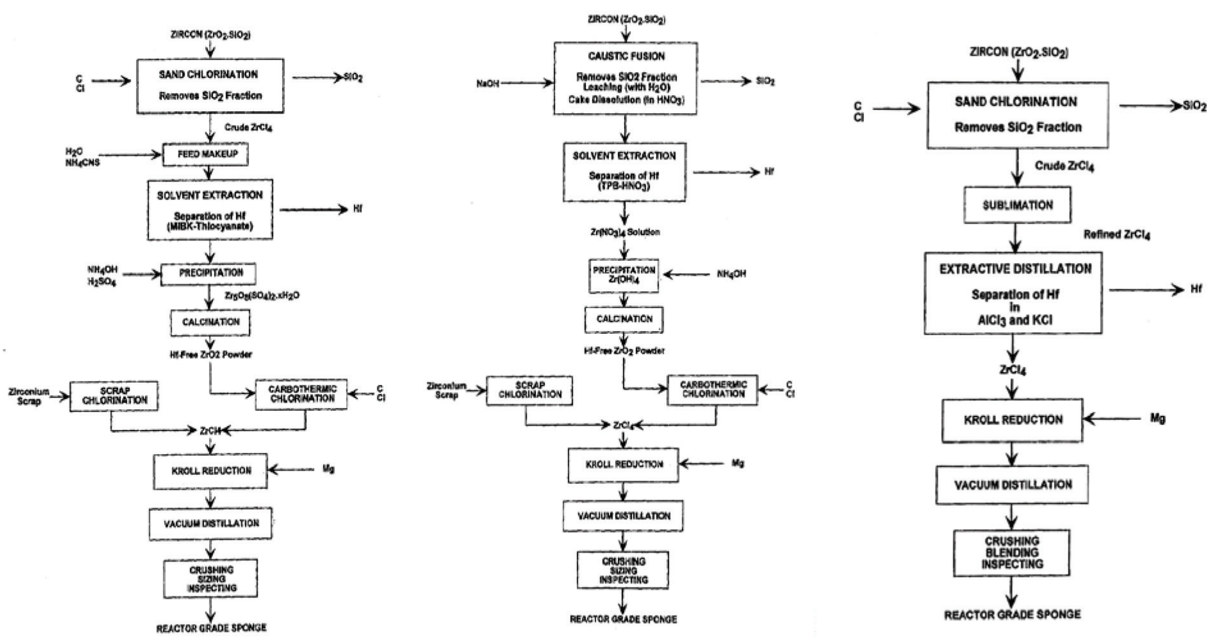

Figure 7 – Process flow sheets for the production of nuclear-grade zirconium of (left) Wah Chang in the USA, (middle) NFC of India, and (right) Cesuz of France (CEA-INSTN, 2008)

- On a regional basis there is, of course the declaration of Africa as a Nuclear Weapon-free Zone, the so-called 'Pelindaba Treaty' originally established in 1996 and finally ratified by the 28th Member State of the African Union on 15 July 2009. This could be offered as a guarantee of the peaceful intentions of such a regional uranium enrichment centre situated in South Africa. Internationally, however, it is to be expected that serious questions will be raised as to whether such a regional treaty is 'watertight' against proliferation.
- The next stumbling block arises from the question: 'What happens to the depleted UF_6 from inter-African 'imported' uranium after enrichment?' Technically, natural uranium imported into South Africa from any other country would be a tradeable commodity, but not the depleted UF_6, which now is most likely labelled as 'hazardous waste'. As a signatory to the Bamako Convention to '*Control the Ban of Imports into Africa and the Control of Transboundary Movement of Hazardous Wastes within Africa*', which was signed on 30 January 1991 in Bamako, Mali and came into force on 10 March 1999, South Africa must abide by its undertaking not to allow the movement of any hazardous waste materials across international borders within Africa. South Africa, in its role of such a regional nuclear fuel centre, would therefore have to remain the host of all of the depleted uranium after the feed material had been converted to UF_6 and then enriched to low enriched uranium (LEU).

➤ Finally, should all of the above political questions be somehow resolved, the technical question of 'international cooperation' *versus* 'go-it-alone' in selecting the technology for enrichment, needs to be understood. Here the lessons from the past should once again be recognized. Yes, South Africa's SET capacity could, in principle, once more go down that road with centrifuge technology, but it will always be a high-risk strategy with the very real possibility of another failure on commercial grounds. The low-risk strategy of using the currently most competitive uranium enrichment centrifuge technology of URENCO under a licence agreement, as France has done for some years, needs to be considered.

Considering all of the above, it seems that a possible South African re-entry into the area of uranium enrichment would be faced with almost insurmountable hurdles, and would need to be very carefully analysed before it is even considered.

The 'small and better' approach for South African SET in materials research

Recognize development trends in commercial power reactor trends

The development of commercial power reactor technology has progressed a long way towards the 'Generation IV' (GEN IV) light water reactor (LWR), with enhanced economy and safety, minimal waste generation, and, last but not least, increased proof against proliferation. South Africa is one of the participating countries in GEN IV and is, therefore, well placed to use this association in planning its nuclear power reactor programme for the future.

Note the key targets of better economy, enhanced safety, less waste, and proliferation resistance. In each of these areas, South Africa's SET capacity can certainly make a 'smaller and better' contribution.

Should South Africa focus its nuclear materials research on in-core or ex-core components?

In considering this question for LWR technology, one inevitably focuses on UO_2 and zirconium-based cladding

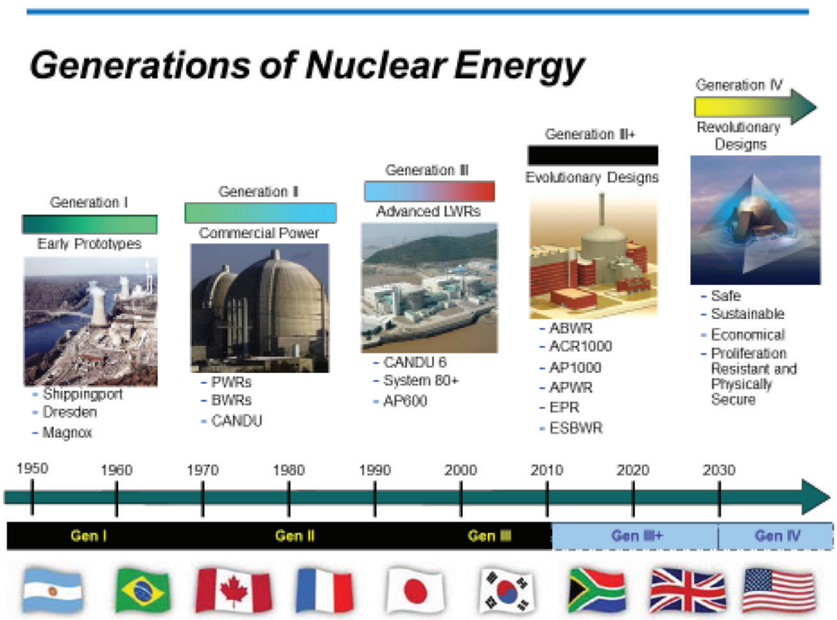

Figure 8 – -The Generation IV LWR development path (US Department of Energy, 2002)

material, but any modifications, even those that are only modest, without ultimate proof of performance under irradiation conditions, would be almost a futile exercise (Figure 6). Is the commercial transfer of in-core technology from a reactor vendor into South Africa an option? Here again, lessons from the past need to be recognized, as in the transfer in the 1980s of Koeberg fuel manufacturing technology from France in Necsa's former BEVA programme. Although the transfer was technically successful (the BEVA fuel elements in Koeberg performed on par with those in France,) the transfer of technology incurred high costs over a period of about four years. At that point, however, the reactor vendor had already moved on with its next, more advanced fuel element design, which would have required another significant investment for South Africa to 'stay in the game', a situation that would recur every few years. The message here is 'don't even consider investing heavily in the local manufacture of critical items in the nuclear island unless a significant percentage of South Africa's electricity generating capacity will be nuclear-based, thus warranting such an investment'.

This raises the obvious question of whether South Africa really needs a reactor such as SAFARI I at all. The answer to this question is an overwhelming YES. South Africa, as one of the top three medical isotope producers in the world, should not relinquish its position. This was achieved under difficult conditions and the replacement of the ageing SAFARI I reactor needs to take that into account. Should 'SAFARI II' then be only an isotope-producing reactor? This would be a very unfortunate retrograde step, as the growing use of SAFARI I for non-nuclear industrial tests such as residual stresses and texture formation in metals, as well as neutron research, constitutes a powerful training and research instrument for South Africa's national SET institutions.

In the '*small and better*' strategy, South Africa's SET capacity should, therefore, rather focus on ex-core components with the general aim of assisting local industry to participate in a meaningful manner in the future nuclear construction programme, but always focusing on the overriding aims of the Generation IV LWR.

Some typical incremental advances with a high impact in the LWR nuclear industry

The development of advanced steels for pressure vessels and steam piping

The steels used for high-temperature steam piping for pressure vessels in both conventional coal- and nuclear-powered generating stations still require better understanding in terms of properties such as creep behaviour, corrosion, weldability, and end-of-life assessment. For instance, the weldability of P91 (nominally a 9%Cr-1%Mo-V-Nb steel) in the Medupi power station required detailed attention to meet the design requirements, and for application in a nuclear power station the welding codes will even be stricter.

The steady improvements in the service performance of P91 (Figure 10) shown below is evidence of 'small and better' improvements over time, achieved only through dedicated research.

Innovative materials science in solving a stress corrosion cracking (SCC) problem through grain boundary engineering (GBE)

Watanabe (1974) once had an 'eureka' moment when he changed the relationship defined by the well-known Hall-Petch equation, that a reduction in grain size leads to the 'holy grail' of higher strength with improved ductility, by asking what would happen if we were to change not the size, but the nature of the grain boundaries. This opened up many studies towards understanding so-called coincident site lattice (CSL) boundaries and how to increase their percentage in a mixture of low- and high-angle grain boundaries (LAGBs and HAGBs), twin boundaries (TBs), and then CSL boundaries. CSL boundaries are high-angle boundaries but possess the special characteristics of LAGBs. The percentage of CSL boundaries can be measured with little difficulty by many modern scanning electron microscopes fitted with an electron backscatter diffraction (EBSD) capability. This innovation is now being applied to the vexing problem of general intergranular stress corrosion cracking (IGSCC) in the tubing of steam generators of PWR stations.

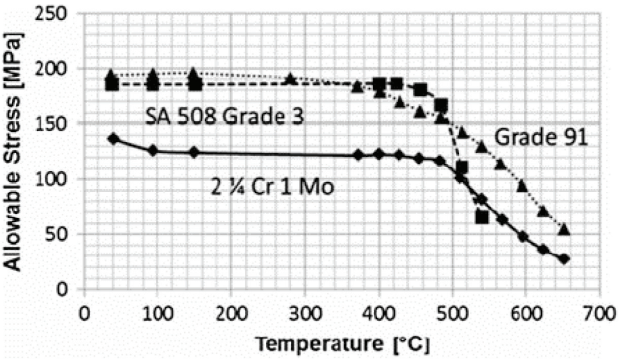

Figure 9 – The allowable operating stresses for a design life of at least 300 000 hours for three steels typically used in LWR technology. SA 508 Grade 3 is a low-carbon manganese-molybdenum steel 'optimized for the nuclear industry. X20 (2.25Cr-Mo steel) and P91 (X10CrMoVNb9-1) are both used for high-temperature steam piping (Buckthorpe, 2002)

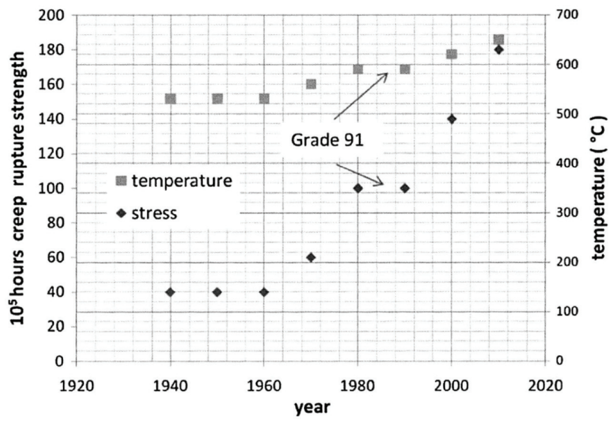

Figure 10 – 100 000-hour creep rupture strength and temperature of 9–12%Cr steels in general over time with the introduction of P91 steel by the late 1980s (Klueh and Harries, 2001)

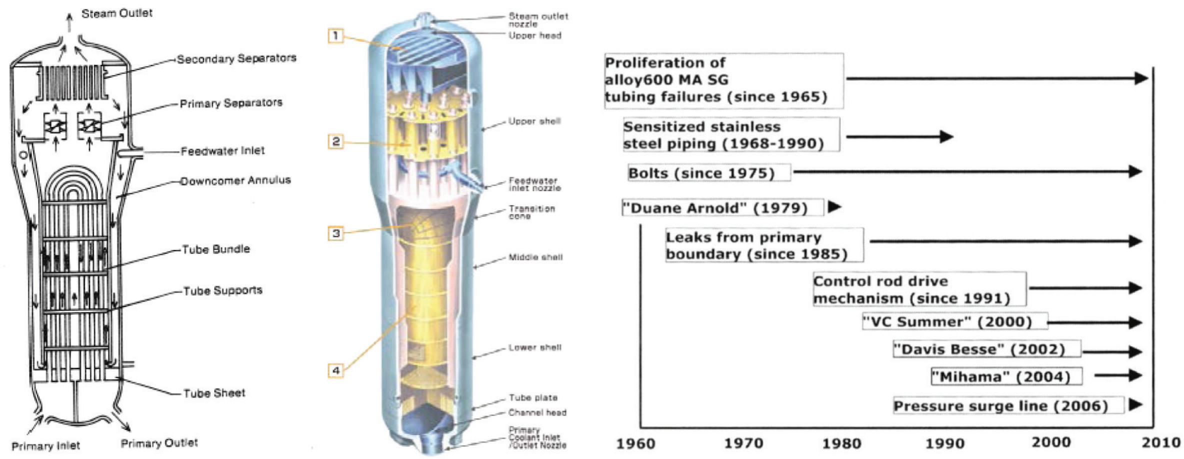

Figure 11 – A schematic cutaway showing the internals of a PWR steam generator (Staehle, 2007) and general corrosion problems experienced in LWR systems with the IGSCC Alloy 600 used in the U-tubes in the PWR steam generators (top of the figure) since the inception of commercial PWR technology (Palumbo, 1993)

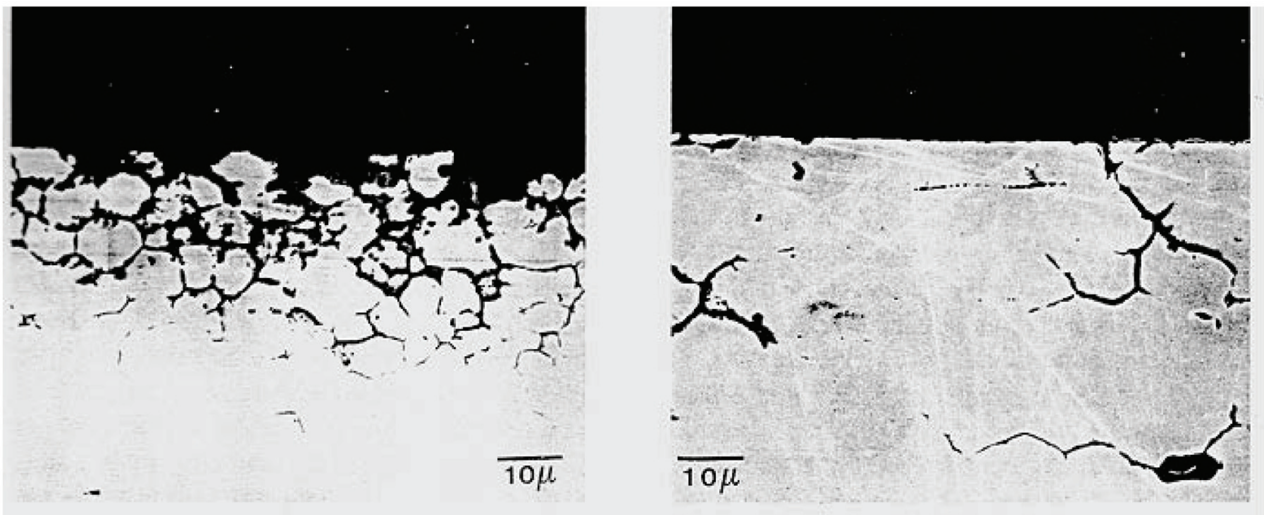

Figure 12 – Alloy 600 (Ni –15.74Cr – 9.1Fe) sensitized for 1 hour at 600°C followed by 120 hours of corrosion testing according to ASTM G28 with (i) its conventional microstructure and (ii) after grain boundary engineering (Lin *et al.*, 1995)

In a number of groundbreaking patents and publications (Palumbo, 1993; Aust, Erb, and Palumbo,1994; Palumbo, Lehockey, and Lin, 1998; Was, Thaveeprungsriporn, and Crawford, 1998), Palumbo and others have found the means to increase the density of CSL boundaries in Alloy 600 (a Ni-16Cr-9Fe alloy) through iterative strain-annealing or iterative strain-recrystallization, typically from less than 10% CSL boundaries in the unprocessed alloy to as high as almost 50% in the iteratively strain-annealed or strain-recrystallized form. Note the very clear micrographic evidence of less grain boundary penetration from the surface for a grain-boundary-engineered Alloy 600 that has been subjected to laboratory-simulated stress corrosion cracking.

Note that in the coarse-grained microstructure in Figure 14, the increase in the CSL boundary density from 20% to 34% was sufficient to dramatically lower the alloy's creep rate at 360°C, while in a fine-grained Alloy 600 the improvement in creep strength appears to be even greater. In both cases, the improvements in creep strength were achieved with a relatively modest increase in CSL boundary density, with no further improvements at higher CSL densities.

Shifting the focus from 'technology' to 'technology plus design and safety'

Up till now, the focus was very much on the technology of nuclear materials, but as Hoeffelner (2011) has shown (Figure 3), this is barely half the story necessary for a resurgence of a national nuclear power programme. The other half will require a significant body of high-level SET capacity with better *understanding* to technically evaluate offers from vendors, ask the right questions, retrieve the required design and performance data, and critically compare differences in design approach from the point of view of:

- Expected performance
- Life assessment

- ➤ The demonstrated safety of the system being offered under all possible external or internal scenarios

before an operating licensing by the NNR (National Nuclear Regulator) can even be considered. In the short term this can be achieved by hiring in nuclear consultants (preferably with no national affiliation with the vendor-country), but this cannot be sustained in the long term for reasons of cost. This approach would also represent a lost opportunity for developing that high-level manpower required for firstly the pre-operational evaluation phase of each offer, then the construction and operational stage of a number of power stations, and finally waste management and the eventual decommissioning of the power stations.

Building up such a body of high-level manpower may appear to be a daunting task, but it is no accident that Hoeffelner (Figure 3) places the technology focus at the point of entry for design and safety assessment. For instance, a postgraduate engineer or scientist who has gained experience in one aspect of the arc welding of zirconium-based cladding material for a Masters or a PhD degree will have absorbed the intricate nature of this alloy far more than in a few months of reading in a library or attending postgraduate courses, without going through the demanding process of an in-depth literature review, research planning and execution, reporting of results, and finally modelling these results in an informative discussion; with all of this being critically reviewed at the end by one or more external examiners from the nuclear industry. In addition, international publications that are peer-reviewed by experts in the field add to demonstrating '*better understanding*'.

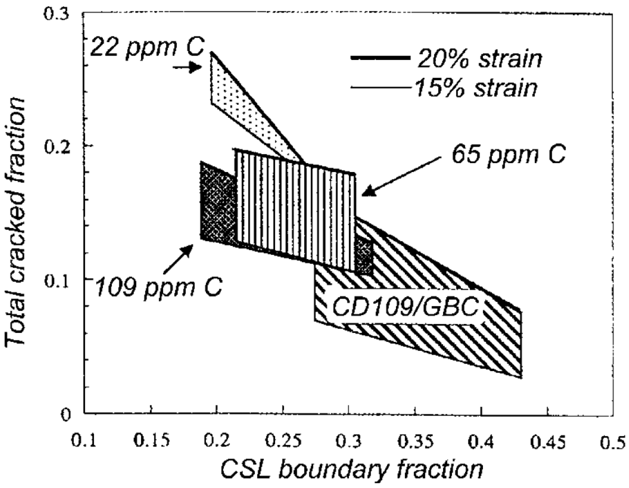

Figure 13 – Dependence of total grain boundary cracked fraction on CSL boundary fraction in Alloy 600 (Ni-16Cr-9Fe) (with varying amounts of carbon in solution and for the case of grain boundary carbides) for strains of 15% and 20% with testing in 360°C PWR primary circuit water at a strain rate of 3 ×10-7 per second (Alexandreanu, Capell, B., and Was, 2001)

However, a basic change will, have to occur in the definition of which materials are nuclear and which are not, as Figure 2 has shown. Nuclear materials in a resurgent nuclear power programme are not simply limited to zirconium, uranium, and a very few others while the rest are seen as 'conventional' and therefore technically outside the current narrow definition of 'nuclear materials'. A steam generator on a PWR can never be viewed as simply another type of heat exchanger, and thereby not warranting the level of regulatory supervision that a nuclear reactor pressure vessel does (and even the latter material is traditionally not viewed, in South Africa at least, as a 'nuclear material'). For reasons of public safety and acceptance/assurance, the process of obtaining an ASME Section III N-certificate on equipment used in a nuclear reactor are far more onerous than if the same equipment is used in a conventional power station. This places most of the materials listed in Figure 2 in an entirely new class, that should be dealt with appropriately.

Some typical areas in the category of '*better understanding*' of an advanced PWR to consider in research could include:

- ➤ Projects that entail the welding of various components, such as fuel cladding, pressure vessel steel, steam piping, steam generator items, *etc.*
- ➤ Projects that entail the strength/ductility/creep/fracture relationships of the above materials at room temperature as well as at typical steam operating conditions
- ➤ Corrosion properties, including IGSS, pitting corrosion,

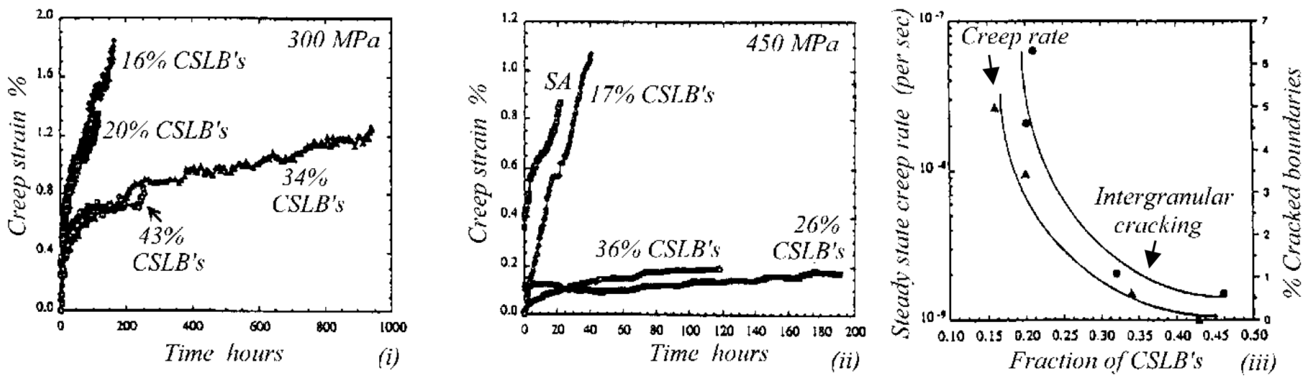

Figure 14 – Constant load creep data on Alloy 600 (Ni-16Cr-9Fe) of a (i) coarse-grained and (ii) a fine-grained microstructure in solution annealed and grain boundary engineered conditions. The creep tests were carried out under argon at 360°C with creep stresses of 300 and 450 MPa respectively. In (iii), the dependence of the steady-state creep rate and the percentage of cracked boundaries on the fraction of CSL boundaries on the coarse-grained material is shown (Was, Thaveeprungsriporn, and Crawford, 1998)

hydriding of zirconium-based cladding, iodine SCC of zirconium alloys, SCC of steam piping and steam generator components, *etc.*

Conclusions

The following aspects need to be incorporated into a national manpower training programme that should be well under way long before the first reactor vendor's technical offer is received.

- Set up a Governmental Advisory Board consisting of the main role-players in an expanded nuclear power programme. These would include Eskom, the NNR, Necsa, senior representatives from industry, public representatives, and the like. The constitution of such a body would, however, have to be very carefully drafted to totally exclude items not associated purely with training of high-level manpower, as any other issue raised in such a forum could compromise the independence of the NNR in ruling on safety issues
- Establish initially at least one (and later possibly a second or third) research centre at a South African university that will undertake the postgraduate training and development necessary for scientists, engineers, and technologists required by the programme. This needs to be done in close association with Necsa
- Ensure that the local R&D effort eschews end-use nuclear materials, but rather focuses on upstream processes in a 'small and better' focus
- Expand Necsa's mandate to include research and development on materials covered by the broader definition of nuclear material. The Advanced Metals Initiative of DST can play a deciding role in overseeing healthy cooperation between the Ferrous Metals Development Network managed on behalf of the AMI by Mintek and the Nuclear Metals Development Network managed on behalf of the AMI by Necsa.

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