7 CONCLUSIONS AND RECOMMENDATIONS

7.1 INTRODUCTION

The title of this dissertation clearly states that the main purpose of the investigation is to evaluate the safety and regulatory aspects associated with a combined nuclear/chemical complex for the production of hydrogen. In order to achieve this objective, all safety and regulatory aspects involved with the combined complex were identified and assessed with respect to their attendant risk as well as probability to impede implementation of the technology. In addition to identifying and evaluating these aspects, the minimum safety distance between the facilities was estimated. The evaluations and estimate of the separation distance were achieved by practising sound engineering judgement on the applicable information obtained during the course of the investigation. With respect to the scope of the investigation, the study focused on a 500 MW_t HTGR such as the PBMR, the use of hot helium gas as intermediate heat transfer fluid and the production of hydrogen or synthesis gas by steam methane reforming (SMR), hybrid sulphur cycle (HyS) and partial oxidation of methane (POX) processes. However, several alternative hydrogen production technologies and nuclear reactors were overviewed since they formed the basis of many investigations that were of fundamental importance to this study. These studies, regardless of how thorough they were conducted, are not universally applicable and knowledge of the specific technologies used in each investigation was required such that their results could be evaluated with regard to this study.

7.2 SUMMARY OF INVESTIGATION

In Chapter 1, the global and South African energy situation with specific reference to the fossil fuel reserves, nuclear energy and hydrogen as secondary energy carrier were reviewed. From this chapter, the following summaries are given:

1. Energy is predominantly obtained from the combustion of fossil fuels, whose finite reserves are quickly being depleted by the energy needs of a growing economy and population. Moreover, fossil derived energy involves the release of large quantities of GHG such as carbon dioxide into the atmosphere, which are devastating the environment, associated with global warming and hazardous to human health. The geo-political sensitivity of the reserves, as well as the current energy industry's dependency upon fossil

fuels gives rise to issues concerning energy security, while the finite nature of the reserves allows for serious concerns regarding sustainable development. However, the reserves (especially that of coal) are huge and could supply energy for a very long time (approximately 150 years). In addition, the direct cost associated with fossil derived energy is relatively low compared to that of renewable energy sources. Therefore, regardless of the disadvantages of fossil derived energy, it will remain the main source of energy, especially for developing countries.

2. Nuclear energy is a very attractive primary energy source that is capable of supplying in the energy requirements of the growing population and economy. It is considered a relatively environmentally benign energy source since it does not release any GHG during operation. However, concerns regarding the permanent storage of radioactive waste are very real and may affect universal implementation of the technology. In addition, the amount of economically recoverable uranium is also finite and may be a concern if a significantly large increase in the amount of fission reactors occur. However, the advantages of nuclear power generation are such that it is almost inconceivable that nuclear energy will not be part of the energy mix of the future. Nuclear energy has the added benefit of being able to supply high temperature heat to various industrial processes, which makes it even more attractive. However, the perceived dangers of nuclear energy by the public, as well as the comprehensive licensing process by the regulatory authorities are significant barriers to the implementation of these technologies.
3. Except for the release of heat upon combustion, hydrogen is an environmentally benign energy source. It is capable of substituting the fossil fuels required by the transport sector, has various industrial applications and is synergistic with electricity. Moreover, the various routes to hydrogen allow it to alleviate concerns regarding energy security and sustainability. However, establishing an infrastructure capable of supplying hydrogen to the so-called hydrogen economy will take a long time and be very expensive. Therefore, the near-term application of hydrogen will most probably be as industrial resource.
4. With regard to the South African energy situation, the Government is vigorously pursuing diversification of energy resources in order to secure energy supply. Nuclear energy is considered a viable alternative to base-load electricity generation and the Government policy regarding nuclear energy is to be completely self-sufficient in the entire life cycle of nuclear energy, as

well as to be a leading international supplier of these technologies and products. Similarly, diversification of energy sources with regard to petroleum (gas in the US) is also under investigation, in which hydrogen may play a vital role. Therefore, the future of nuclear power, and possibly hydrogen production, is very promising in the South African political context, at least for the near-term future.

In Chapter 2, high-temperature gas-cooled nuclear reactors (HTGRs), the leading candidates thereof, and the various nuclear-assisted hydrogen production technologies were examined. From this chapter, the following summaries are given:

1. The unique characteristics of Gen-IV HTGRs allow them to be considered as inherently safe. Inherently safe reactors adhere to four principles of stability (nuclear, thermal, chemical and mechanical) such that no accident could result in core damage or the corresponding release of fission products (radioactive material) to the environment. To this extent, these HTGRs could be classified as "catastrophe-free" technologies.
2. HTGRs are thermal (neutron spectrum) nuclear reactors with pebble-bed or prismatic block core designs that use inert helium as coolant medium and graphite as moderating medium. The designs of the core and fuel elements allow high operating temperatures to be achieved, while still adhering to the principles of stability.
3. The PBMR technology is considered the leading Gen-IV HTGR candidate, although the HTTR (30 MW_t) and HTR-10 (10 MW_t) research reactors have already been operated safely. It seems that licensing of a pebble-bed nuclear reactor could be extensive due to the statistical packing and operating of the reactor. In this regard, the current nuclear regulations are based on PWR and BWR technologies, which are radically different from HTGR technologies and could be problematic.
4. Considering nuclear-assisted hydrogen production technologies, electrochemical, thermochemical and hybrid thermochemical options are available. Each option has its advantages and disadvantages. The most important aspects are those of efficiency, hazardous chemical inventory, technological feasibility and separation distance from the nuclear reactor. The hybrid and thermochemical technologies have higher efficiencies, but have significant hazardous chemical inventories and require being near the HTGR in order to reduce heat losses. However, the disadvantages associated with

hybrid and thermochemical technologies are being addressed to such an extent that their increased efficiencies allow them to be the leading candidates.

5. The steam methane reforming process is the only near-term option due to the industrial maturity of the process. However, the use of a fossil fuel (methane or natural gas) as feedstock and the corresponding release of carbon dioxide make this option unfavourable in the long-term, regardless of whether CCS is employed. Similarly, the use of methane in the partial oxidation and plasma-arc reforming processes limit their long-term applicability.
6. The remaining leading candidates are the hybrid sulphur cycle (HyS) and the sulphur-iodine cycle (I-S). They have comparable efficiencies, but the presence of iodine, hydrogen iodide and hydriodic acid in the I-S cycle may result in the HyS being preferred.

In Chapter 3, the physical and chemical properties of the hazardous substances present in the different hydrogen production technologies were examined. The primary focus was on hydrogen, methane and carbon monoxide, but all hazardous substances were discussed to some extent. From this chapter, the following summaries are given:

1. Hydrogen can be a very dangerous substance if not used appropriately. It is a chemical asphyxiant, has very wide flammable and detonation ranges, a high tendency to leak, and is able to diffuse through intact metals causing hydrogen embrittlement. Hydrogen's very low density is its most important safety characteristic since it allows hydrogen to be rapidly dispersed into the surrounding atmosphere, thereby reducing the amount of hydrogen available to combust as well as the consequences of combustion. Hydrogen fires have a very high flame temperature, but due to its low emissivity the attendant risk is relatively low. However, hydrogen detonations generate high peak pressures that can have severe consequences, but this event requires a high degree of congestion or containment, which is unlikely at the production facility. Hydrogen embrittlement is of some concern considering the long operating lifetime of the facility, but appropriate material selection and regular inspection and maintenance programmes will reduce the probability of it being a hazard. Therefore, the properties of hydrogen will not be a barrier to the implementation of a nuclear/chemical complex.

2. Methane is also flammable and detonable, but over a smaller concentration range than hydrogen. However, due to methane being significantly heavier-than-air it is much slower to disperse into the surrounding atmosphere and tend to form ground-hugging clouds. These clouds could travel considerable distances to be ignited and due to its low dispersion rate, the flammable content in a methane gas cloud is much higher than that of hydrogen. Furthermore, methane fires have a significantly higher emissivity than hydrogen fires, which make its attendant risk comparably high although its flame temperature is lower than that of hydrogen's. Upon combustion, it generates peak pressures lower than that of hydrogen, but due to its higher emissivity and formation of ground-hugging gas clouds, it is considered a greater safety hazard than hydrogen.
3. Similar to methane and hydrogen, carbon monoxide is flammable and detonable. At ambient conditions carbon monoxide is only slightly lighter-than-air, which results in a slow diffusion rate and the possibility to form a gas cloud that tends to lie near ground level. However, the distance this cloud could travel is significantly less than that of methane. Furthermore, carbon monoxide is extremely toxic and poses a significant threat to operating personnel, especially considering its capacity to travel some distance from the point of being released. Therefore, depending on the amount produced at the facility, it is considered a significant safety hazard to both operating personnel and the plant structures and components.
4. Oxygen is produced as by-product in many of the thermochemical and hybrid technologies and due to its extreme capability to cause fires it is considered a significant safety hazard. Oxygen is a prerequisite of any flammable or detonation hazard and the greater the concentration thereof, the greater the consequences associated with these hazards. Moreover, many materials are highly susceptible to combustion when exposed to oxygen-rich atmospheres, especially at high temperatures. Additionally, oxygen is heavier-than-air and is able to form ground-hugging gas clouds that can travel significant distances to influence or instigate hazards. Therefore, oxygen is considered a significant safety hazard and will play a vital role in the development of the combined complex. Fortunately, oxygen is generally separated from the hydrogen product at a relatively early phase of the separation cycle and can be routed and stored away from the flammable product to reduce the risks associated with oxygen.

5. The corrosive substances (sulphuric acid, sulphur dioxide, sulphur trioxide, iodine, hydrogen iodide and hydriodic acid) significantly increase material requirements, especially considering the operating lifetimes of the facility, as well as posing a threat to human health and the environment. Many of these substances react with some metals to form hydrogen; however, the amount of hydrogen produced thereby does not result in a significant flammable hazard. All of these corrosive substances are heavier-than-air and form ground-hugging gas clouds that can travel significant distances to affect plant structures and operating personnel. However, the most important hazard associated with corrosive substances is that of material durability and reliability. Especially the iodine compounds pose severe material requirements and may be considered as barriers to the implementation of the technology associated with it.

In Chapter 4, the accident phenomena and propagation methods associated with the hazards identified in the previous chapter were investigated. From this chapter, the following summaries are given:

1. The evolution of a flammable gas cloud included jet releases, molecular diffusion, three-dimensional dispersion and discrepancies due to real gas behaviour as opposed to ideal gas behaviour. Jet releases occur when a pressurized gas is released through a hole or aperture from its containment, whereas molecular diffusion takes place due to concentration-, temperature- and pressure gradients and is responsible for the diffusion of hydrogen through metals. Three-dimensional dispersion of gas clouds considers issues such as the containment and ambient conditions, atmospheric turbulence (wind) and degree of congestion of the environment into which it is released. The most notable observation associated with three-dimensional dispersion is that the buoyancy of the gas is essential only at low wind velocities, at higher wind velocities the gas behaves as a neutral gas and is dispersed accordingly. Real gas clouds differ significantly from the ideal gas cloud models. Where ideal gas clouds are hemispherical, real gas clouds are of pancake form, therefore covering a larger area but containing the same explosive inventory, in some cases at higher concentrations due to gravity and atmospheric conditions. These differences do not significantly affect the magnitude of the peak pressure generated during combustion, but the pulse

duration is much shorter (more damaging) and propagates further for real gas cloud combustions.

2. Combustion of flammable substances considers laminar and turbulent premixed and diffusion flames, as well as the general types of combustion including fireballs, UVCEs, deflagrations, detonations and DDTs. The most probable outcome resulting from the unintended release of a flammable substance and its corresponding ignition is a fireball or deflagration. During unconfined hydrogen-air combustions, the energy of combustion is in the range of 0.1 – 10 % of the thermal energy content of the gas cloud, usually less than 1%.
3. The blast waves (peak pressures) generated by deflagrations differ significantly from that of detonations. Deflagration and detonation blast waves differ in peak overpressure, duration of the pressure impulse, steepness of the wave front, and in the decrease of overpressure with propagation distance. Peak overpressures of deflagrations are usually less than 10 kPa, while detonations are in the MPa range, depending on the specific combustion scenario.
4. The amount of heat radiated from a fire depends on various aspects, but on average, the fraction of combustion energy released as thermal radiation is 17 – 25 % for hydrogen-air mixtures and 23 – 33 % for methane-air mixtures. The most important aspects of heat radiation are the emissivity of the fuel and the moisture content of the environment in which the fire takes place.

In Chapter 5, all aspects pertaining to the nuclear/chemical complex, with special relevance to the safety thereof, were examined and included investigating international R&D projects, the available interfacial equipment and connection technologies and previous safety evaluations of similar nuclear/chemical complexes. From this chapter, the following summaries are given:

1. The major research and development projects concerning nuclear-assisted production of hydrogen include PBMR (SA), ANTARES (France), GTHHTR300C (Japan), NHDD (Korea) and NGNP (USA). Similarities in the design and layout of these projects include the use of an intermediate heat exchanger (IHX), underground placement of the nuclear reactor, safety distances, an earthen mound between the facilities and storage of the product(s) at the outer perimeters of the plant.

2. The compatibility of the plants was assessed according to power, heat, peak temperature and temperature range of delivered heat, pressure of the heat transfer loops, physical and process isolation of the plants and tritium contamination of the product cycle. With respect to these requirements, the combined complex is compatible and feasible.
3. In the interfacial equipment section, different concepts under development regarding the IHX, nuclear steam reformer, hot gas duct and high-temperature isolation valve were examined. The technological and materials requirements of these equipment are extremely severe considering their long operating lifetimes and extreme operating conditions (high temperature, high pressure, corrosive substances). Of significant importance are the consequences associated with failures of the abovementioned equipment.
4. The safety of the combined complex was discussed according to hazard identification (HAZOP), probabilistic safety assessments (PSA) and plant phenomena identification and ranking tables (PIRTs). The hazard identification was based on tritium contamination, thermal turbulences in the systems, the release of flammable and hazardous substances, and the separation distance requirements. In this regard, the tritium contamination was considered a minimal safety hazard, thermal turbulences of concern to the control, operability and efficiency of the plants, while the release of flammable and hazardous substances and the separation distance requirements are of major concern to the safety of the combined complex. The last two aspects are interrelated such that if the separation distance is sufficient, the release of flammable and hazardous substances at the chemical plant will have no significant impact on the safety of the nuclear plant. However, from a thermal hydraulic perspective the plants need to be as close to each other as possible to reduce thermal losses incurred during the transport of heat to the chemical plant. In contrast, from a regulatory point of view the plants should be separated by a sufficiently large distance to ensure and promote safety of the nuclear plant.
5. A PSA study regarding the separation distance indicated that a minimum separation distance of 110 m are required to obtain an increase in CDF of 10^{-6} per year, which is an acceptable risk according to risk-informed design criteria.
6. A PSA study on the HTTR/SMR system utilized a HAZOP study to identify the main initiating events that could result in the loss of human life. The three main initiating events considered was a methane pipe break, a helium duct rupture and a heat exchanger tube break in the primary water cooling system of the HTTR. The results of this study show that the most hazardous event with regard to the

loss of human life is that of a methane pipe break resulting in a methane explosion. In addition, the study shows that an accident at one of the plants has little effect on the other due to the design base distance between the plants, the fact that the reactor is underground, as well as other safety characteristics of the nuclear power plant.

7. The PIRTs investigated chemical releases at the chemical plant, process thermal events, heat transport system failures and nuclear reactor events that could influence the chemical facility, which in turn could have feedback to affect the nuclear plant. The study concluded that oxygen releases, IHX and PHX failures, loss of intermediate heat transfer fluid and ingress of foreign media into the primary system of the nuclear reactor are of high importance to the safety of the operating personnel and the safety functions of the nuclear plant.

In Chapter 6, the regulatory aspects that may influence the licensing of the combined nuclear/chemical complex were examined. In South African Law, nuclear energy is governed by the Nuclear Energy Act (46 of 1999), nuclear installations by the National Nuclear Regulator Act (47 of 1999) and hazardous substances by the Hazardous Substances Act (15 of 1973). It is important to note that it is not the purpose of this section to investigate the licensing of either the nuclear plant or the chemical facility, but rather to investigate what regulations may come into play when these facilities are connected and co-located. Therefore, it was assumed that both facilities, as stand-alone plants, are regulatory-approved and adhere to regulations without co-location and connection. From this chapter, the following summaries are given:

1. The Nuclear Energy Act (46 of 1999) establishes Necsa as governing authority to govern the acquisition of restricted material and equipment, manage radioactive waste and adhere to protocols regarding nuclear non-proliferation. With regard to this study, the act has little relevance except for Necsa being responsible for research and development regarding nuclear activities.
2. The National Nuclear Regulator Act (47 of 1999) establishes the NNR as governing authority to regulate nuclear activities and provide for safety standards and regulatory practices for protection of persons, property and the environment against nuclear damage. This Act is of great significance to this study considering its provision of safety standards (dose constraints and probabilistic risk limits). However, the requirement documents and licensing

documents are reviewed by a case-by-case basis on the specific plant to be licensed, which falls outside the scope of this investigation since complete design information is not available. However, it is clear from the Act that the chemical facility will be subject to investigation and (possibly) control by the NNR.

3. The licensing process of HTGR- and associated nuclear-hydrogen production technologies in South Africa is not at a stage where it can be evaluated with respect to the successful implementation of these technologies.
4. The Hazardous Substances Act (15 of 1973) provides for the control of substances that may be hazardous to human beings, to divide these substances into groups according to their risk and influence to humans and to regulate actions regarding these substances. With respect to the study at hand, the hydrogen product may be considered as a Group IV hazardous substance due to its radioactive constituent (tritium), although this is very unlikely due to the product's very low radioactivity.
5. US regulatory requirements that may be influential considering the combined complex are risk-informed applications (RG 1.174), habitability of the control room (RG 1.78) and quantity distance relationships regarding flammable substances (RG 1.91).
6. In the EU, the main regulations associated with the use and production of hydrogen (Seveso Directives I and II) would have to be revised in order to obtain permission for a combined nuclear/chemical complex.

7.3 CONCLUSIONS

In light of the information given in the preceding section, and considering their importance with regard to the successful research, development and implementation of a combined nuclear/chemical complex for the production of hydrogen, the following conclusions can be made:

- Although very dangerous, it is a misconception that hydrogen is the most hazardous substance present at the chemical facility and it is not expected to significantly influence the overall safety of the combined complex. However, from a regulatory perspective it will be very important due to quantity distance relationships as associated with flammable substances.

- The presence of hazardous, heavier-than-air substances at the chemical facility will play a vital role in the licensing process as well as in the overall safety of the complex. Heavier-than-air gas clouds are able to affect plant components and structures as well as humans and the environment at great distances beyond the point of release, which makes them of special concern.
- Oxygen is an especially important substance due to its extreme capability to cause fires, promote the propagation of flames and detonations, as well as increasing the consequences associated with these hazards.
- The flammability hazard and associated consequences due to hydrogen combustions at the chemical facility do not pose significant threats to the nuclear plant considering the most probable outcome of this event. The combustion energy released during this event will usually be less than 1 % of thermal energy content of the gas cloud, of which only a 17 - 25 % will be emitted by thermal radiation, and will result in a blast wave of approximately 10 kPa, all of which decays significantly over the distance to the nuclear plant.
- The applicability of current nuclear regulations is of significant concern with respect to HTGR technologies and nuclear-assisted production technologies.
- Public acceptance of both nuclear energy and the proposed nuclear-assisted production of hydrogen will be major issues to address if the technologies are to be implemented.
- The safety of products produced by nuclear-assisted production technologies will be very important to the consumers, especially the perceived safety thereof will be of utmost importance.
- The durability and safety of the interfacial equipment involved with the technology will be fundamental in the successful implementation of the technology. The IHX is of utmost importance due to the consequences failure thereof will have.
- From the safety aspects identified and investigated in this project, none of them is insurmountable such that sufficient research and development could not be able to address them.
- From a regulatory perspective, current nuclear regulations may be barriers to the implementation of nuclear-assisted hydrogen production technologies, however, it is expected that more applicable regulations will be implemented to govern these facilities.
- The separation distance between the nuclear plant and hydrogen production facility will most probably not be according to current regulations since these

are very severe and will affect the technical and economical feasibility of the combined complex.

- A multiple barrier system regarding separation of the two critical facilities is proposed consisting of underground placement of the nuclear reactor, employment of an earthen mound between the facilities, and a sufficient safety distance of approximately 110 m.
- Storage of oxygen and flammable substances such as hydrogen, methane, natural gas and synthesis gas should be at the outer perimeters of the plant, with the storage of oxygen sufficiently separated from the storage of the flammable substances.
- Proper materials selection and even development and testing of "new" materials will be of fundamental importance to the success of the combined complex, especially considering the extreme operating conditions, corrosive environments and extensive operating lifetimes.
- The relatively early phase of licensing a HTGR or associated process heat application technology in South Africa does not allow the study to evaluate the licensing capability of these technologies. However, this should not be considered as disconcerting since it allows industry to take part in the licensing process and address licensing issues as they arise. Moreover, it allows the licensing process to be a concomitant effort by the regulatory authorities and industry to develop applicable and efficient regulations.
- At this stage, the nuclear regulatory authorities of most countries are not prepared for the implementation of nuclear-hydrogen production on an industrial scale. Germany is of particular concern since current regulations want to phase out all nuclear technologies. However, it seems that the Asian countries (Japan, China, and Korea) may be more accommodating to the implementation of these technologies.

7.4 RECOMMENDATIONS

In light of the conclusions given in the preceding section, and considering that successful implementation of any of these technologies still require significant research and development, the following recommendations are given:

- Perform a complete HAZOP study on the specific nuclear/chemical complex in order to identify specific events that could result in the loss of human life, affect the safety systems of both plants or induce hazards that can result in a nuclear incident or accident.
- Perform a complete PSA study on the specific nuclear/chemical complex under consideration in order to quantify the risks associated with the complex. Moreover, this will be a requisite of the licensing process and will serve to promote public acceptance of the technology.
- Perform durability tests on the materials proposed to be used for the IHX and PHX, specifically under the process operating conditions and corrosive environments.
- Construct test facilities to simulate the technology and assess the control and operability of the combined complex.
- Construct test facilities of the thermochemical production plant, with emphasis on the process heat exchangers (reactors utilizing the process heat supplied by the nuclear reactor through the intermediate heat transfer loop).
- Develop regulations specific to process heat applications of nuclear reactors, with specific emphasis on the use of HTGRs as nuclear reactors.
- Develop regulations pertaining to the use of products produced by nuclear-assisted technologies.
- Establish public relation departments to aggressively promote the safety of nuclear energy and nuclear-assisted production technologies, and alleviate concerns regarding nuclear waste management, transport of radioactive material and the probability of having another Chernobyl-type accident.
- The perceived dangers associated with radioactive material will be fundamental and the public should be informed of their current exposure to naturally radioactive (environmental radiation) materials such that their concerns with the nuclear-produced products can be alleviated by comparing it to what they are currently exposed to.