Evaluating the safety and regulatory aspects of the combined nuclear/chemical complex for Hydrogen production

By

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Dissertation submitted in partial fulfilment of the requirements for the degree

Master of Engineering

at the Post-Graduate School of Nuclear Science and Engineering of the North-West University, Potchefstroom Campus

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November
2008

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Abstract:

Recently there has been an exceptional resurgence of interest in the nuclear power industry and the cogeneration of hydrogen from nuclear process heat and electricity, with climate change and energy security the main drivers for the implementation of these technologies. Nuclear-assisted hydrogen production technologies include electrochemical, thermochemical and hybrid-thermochemical options that respectively require electricity, high-temperature process heat and both electricity and high-temperature process heat from the nuclear reactor. Although the current commercial fleet of nuclear reactors are able to supply in the requirements of the electrochemical technologies, high-temperature nuclear reactors (HTR) are required for the thermochemical and hybrid-thermochemical options. The unique safety characteristics of Gen-IV HTGR technologies, such as the PBMR, favour their use in future energy-generation scenarios, especially with regard to process heat applications. Hydrogen production as process heat application is uniquely capable of alleviating concerns regarding energy security and sustainable development while supplying in the energy requirements of a growing population and economy. Hydrogen is relatively environmentally benign as fuel constituent or secondary energy carrier in the so-called hydrogen economy and is able to complement or even substitute fossil fuels in future energy markets, especially in the transport and industrial sectors. Regardless of the benefits of nuclear-assisted hydrogen production technologies, barriers ranging from technological and economical feasibility to safety and regulatory concerns exist that require to be addressed if these technologies are to be successful. In this regard, the purpose of the study is to investigate all safety and regulatory aspects associated with a combined nuclear/chemical complex such that they may be evaluated according to their attendant risk and probability to impede implementation of the technology. Of fundamental importance is the connection and co-location of the two critical facilities, especially considering the hazardous chemical inventories present at the chemical facility, the consequences of a nuclear accident and the use of the final product (hydrogen) by consumers.

Titel: Evaluering van die veiligheids- and regulatoriese aspekte verbonde aan 'n gekombineerde kern-chemiese kompleks wat verantwoordelik is vir die produksie van waterstof

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Uittreksel:

Onlangse hernieude belangstelling in kernenergie en die meegaande produksie van waterstof met behulp van die proseshitte en elektrisiteit gelewer deur die kernreaktor, is meerendeels weens bekommernisse rakende klimaatsveranderinge en energiesekuriteit. Kernbehulpte waterstofproduksietegnologieë sluit elektrochemiese, termochemiese en hibried-termochemiese opsies in wat onderskeidelik elektrisiteit, hoë-temperatuur proseshitte en beide elektrisiteit en hoë-temperatuur proseshitte van die kernreaktor verlang. Alhoewel die huidige kommersiële floot kernreaktore aan die vereistes van die elektrochemiese opsies voldoen, word hoë-temperatuur kernreaktore benodig vir die termochemiese en hibried-termochemiese opsies. Die unieke veiligheidseienskappe van die Generasie IV hoë-temperatuur gasverkoelde kernreaktortegnologieë, soos die PBMR, begunstig hul gebruik in toekomstige energie-opwekking scenarios veral ten opsigte van proseshittetoepassings. Waterstofproduksie as proseshittetoepassing is uniek om bekommernisse rakende energiesekuriteit en volhoubare ontwikkelinge te verminder terwyl dit kan voorsien in die energie behoeftes van 'n groeiende populasie en ekonomie. Waterstof is relatief omgewingsvriendelik as brandstofkomponent of as sekondêre energiedraer in die sogenaamde waterstofekonomie. Dit kan komplimentêr tot aardbrandstowwe gebruik word of selfs vervanging daarvan bewerkstellig in toekomstige energiemarkte, veral in die vervoer- en industriële sektore. Ongeag die voordele van kernbehulpte waterstofproduksietegnologieë, is daar verskeie struikelblokke wat uit die weg geruim moet word alvorens die tegnologieë suksesvol toegepas kan word. Dit sluit aspekte rakende tegnologiese- en ekonomiese haalbaarheid tot veiligheids- en regulatoriese kwessies in. Vervolgens is die doel van die studie om alle veiligheids- en regulatoriese aspekte wat verband hou met die gekombineerde kern/chemiese kompleks te bestudeer volgens hul bydraende veiligheidsrisiko en die moontlikheid om implimetering van die tegnologie te belemmer. Die koppeling en ko-plasing van die twee kritiese fasiliteite is van kardinale belang veral in ag genome die inventaris van gevaarlike stowwe by die chemiese aanleg, gevolge van 'n kernogeluk en die gebruik van die finale produk (waterstof) deur verbruikers.

ACKNOWLEDGEMENTS

Foremost I would like to thank my Creator for His Grace and for allowing me the opportunity, the means and perseverance to achieve a lifelong goal.

Nothing worthwhile is ever achieved in a vacuum, and to this extent, the author would like to acknowledge and express appreciation to the following people, without whom this experience would not have been possible and certainly not meaningful:

- Professor Blom for his expert guidance, belief in me and allowing me this opportunity;
- My mother Marthie for her prayers, enduring love, continuous support and all the sacrifices she had to make;
- My sisters Marli and Elizmari for their moral support, belief in me and making me realize what is truly important in life;
- My father Gert for building my character and teaching me the true meaning of having responsibilities, honour and morality, but who was sadly taken away from us before he could see me reach this milestone;
- My dear friend Lieslmari Lamprecht for her love, moral support and belief in me as well as being by my side every step of the way;
- All my friends, especially Dries Grundlingh, Bennie Repsold and MD Coetzee, for helping me keep a healthy balance between work and fun – we had the time of our lives.

Lastly, the author would like to acknowledge science and the attaining of knowledge as driving forces in his life, while keeping in mind that:

"It would be possible to describe everything scientifically, but it would make no sense; it would be without meaning, as if you described a Beethoven symphony as a variation of wave pressure."

-- Albert Einstein –

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TABLE OF ABBREVIATIONS & ACRONYMS

Abbreviation or Acronym	Description
AHTR	Advanced High-Temperature Reactor (US)
ACGIH	American Conference of Government Industrial Hygienists
ACS	Auxiliary Cooling System (HTTR-30)
AVR	Arbeitsgemeinschaft Versuchs-Reaktor (Germany)
BISO	Double (Binary) coated fuel particles
BLEVE	Boiling Liquid Evaporating Vapour Explosion
BMI	Bundesministerium des Innern (German Regulation)
BP	Boiling Point
BRHS	Biennal Report on Hydrogen Safety
BWR	Boiling-Water Reactor
CCS	Carbon Capture and Storage
CDF	Core Damage Frequency
CJ	Chapman-Jouguet
CNS	Central Nervous System
CTL	Coal-to-Liquid
DDT	Deflagration-to-Detonation Transition
DME	Department of Minerals and Energy (South Africa)
DOE	Department of Energy (US)
DOH	Department of Health (South Africa)
DRI	Direct Reducted Iron
EAF	Electric-Arc Furnace
EOS	Equation of State
EU	European Union
FCV	Fuel-cell Vehicles
FOM	Figure-of-Merit
FP	Fission Products
FZK	Forschungszentrum Karlsruhe – Research Centre Karlsruhe
GA	General Atomics
GAO	Government Accountability Office (US)
GDP	Gross Domestic Product
Gen-IV	Generation IV Nuclear Reactors
GG	Government Gazette (South Africa)
GHG	Greenhouse Gases
GT-MHR	Gas-Turbine Modular Helium Reactor
H2-MHR	Modular Helium Reactor with Hydrogen cogeneration (US)
HAZOP	Hazard and Operability Study
HDI	Human Development Index
HT	High-Temperature
HTE	High-Temperature Electrolysis
HTGR	High-Temperature Gas-cooled Reactor
HTR	High-Temperature Reactor
HTR-Modul	Modular High Temperature Reactor (Germany)
HTSE	High-Temperature Steam Electrolysis
HTTR	High-Temperature Engineering Test Reactor (Japan)
HyS (also known as WSP)	Hybrid-Sulphur cycle
IAEA	International Atomic Energy Association
ICE	Internal Combustion Engine
IEA	International Energy Association
IHX	Intermediate Heat Exchanger
INSC	International Nuclear Societies Council
I-S (or I-S)	Iodine-Sulphur cycle

JAEA	Japan Atomic Energy Agency
JAERI now JAEA	Japan Atomic Energy Research Institute
KLAK	Kleine Absorberkugeln
KVK	Komponenten-Versuchskreislauf (Components Test Circuit)
LFL	Lower Flammability Limit
LOCA	Loss of Coolant Accident
LTWE	Low-Temperature Water Electrolysis
LWR	Light-Water Reactor
MCS	Main Cooling System (HTTR-30)
MEDUL	Mehrfach & Durchlauf (Multi pass through put)
MESG	Maximum Experimental Safe Gap
MHR	Modular Helium Reactor
MMI	Methane-Methanol-Iodomethane thermochemical cycle
MP	Melting Point
Mtoe	Mega tonne oil equivalent
NASA	National Aeronautic and Space Administration (US)
Necsa	South African Nuclear Energy Corporation
NFPA	National Fire Protection Agency (US)
NGNP	Next-Generation Nuclear Plant (US)
NHI	Nuclear-Hydrogen Initiative
NHDD	Nuclear Hydrogen Development and Demonstration project (Korea)
NIOSH	National Institute for Occupational Safety and Health (US)
NNR	National Nuclear Regulator (South Africa)
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Committee (US)
NTP	Normal Temperature and Pressure
ORNL	Oak Ridge National Laboratories (US)
OSHA	Occupational Safety and Health Administration (US)
OTTO	Once-Through-Then-Out
PBMR	Pebble-Bed Modular Reactor (SA)
PCHE	Printed Circuit Heat Exchanger
PCU	Power Conversion Unit
PEM	Proton Exchange Membrane
PENS	Peak Electricity Nuclear System
PFHE	Plate Fin Heat Exchanger (France)
PHHP	Process Heat and Hydrogen Production
PHHP	Process Heat Hydrogen Production
PHPS	Primary Helium Purification System (HTTR)
PHX	Process Heat Exchanger
PIRT	Phenomena Identification and Ranking Table
PNP	Prototype Plant Nuclear Process Heat Project (Germany)
POX	Partial Oxidation of Methane
ppm	Parts per million
PRD	Pressure Relief Device
PSA	Probabilistic Safety Assessment
PWC	Pressurized Water Cooler (HTTR-30)
PWR	Pressurized-Water Reactor
PyC	Pyrolytic Carbon
QD	Quantity-Distance
R	Regulation (South Africa by notice in Gazette)
R&D	Research and Development
RBMK	Reaktor Bolchoi Mochtchnosti Kanalni (Russia)
RG	Regulatory Guide (US regulation)

RPV	Reactor Pressure Vessel
SAS	Small Absorber Spheres
SCRAM	Safety Control Rod Axe Man
SG	Steam Generator (HTTR)
SH	Super Heater (HTTR)
SHPS	Secondary Helium Purification System (HTTR)
S-I (or I-S)	Sulphur-Iodine cycle
SiC	Silicon Carbide
SMR	Steam Methane Reforming
SNL	Sandia National Laboratories (US)
SR	Steam Reformer (HTTR)
SRNL	Savannah River National Laboratories (US)
SSC	Systems, Structures and Components
STP	Standard Temperature and Pressure
Tetryl	N,2,4,6-Tetranitro-N-methylaniline
THTR	Thorium High Temperature Reactor (Germany)
TMI	Three Mile Island (US)
TNO	Organization for Applied Scientific Research and Development (Netherlands)
TNT	Trinitrotoluene
TRISO	Triple coated fuel particles
UFL	Upper Flammability Limit
UN	United Nations
UNDP	United Nations Development Programme
UVCE	Unconfined Vapour Cloud Explosion
VCS	Vessel Cooling System (HTTR-30)
VHTR	Very High-Temperature Reactor
WCED	World Commission on Environment and Development
WGS	Water-gas-shift (reactor)
WSP (also known as HyS)	Westinghouse-Sulphur Process

TABLE OF NOMENCLATURE

Symbol	Description	Dimensions
A	Cross sectional area	m^2
c	Sonic velocity of gas	m/s
C	Molar concentration	mol/cm^3
C_p	Specific Heat Capacity (at constant pressure)	J/g.K or cal/g.K
C_v	Fuel caloric value	kg/kJ
D	Distance from flame	m
d	Discharge diameter	mm
D_{ij}	Diffusion coefficient	cm^2/s
E	Energy	W
F	Fraction of combustion heat radiated	[-]
f_t	Empirical turbulence factor	[-]
I	Intensity	$J/cm^2.s$
j	Flux	$kg/s.cm^2$
K	Constant	[-]
K_r	Allowable radiation level	[-]
K_a	Acidity Constant	[-]
L	TNT equivalent of explosive substance	kg
M	Molecular weight	kg/mol
m	Mass flow rate	kg/s
p	Pressure	Pa
P	Thermal Power	W
$P*$	Reactivity	%, cent, $
R or r	Distance	m
T	Temperature	K or ^0C
t	Time	s
u	Velocity	m/s
V	Volume	m^3
W	TNT equivalent of explosive substance	kg
W_b	Burning rate	kg/s
w	Water vapour % by weight	%
x	Distance from nozzle	m

Symbol (Greek)	Description	Dimensions
α_T	Coefficient of reactivity (Temperature)	K^{-1}
α	α-particle (Radioactive decay)	[-]
β	β-particle (Radioactive decay)	[-]
γ	γ-particle (Radioactive decay)	[-]
ε	Emissivity	[-]
ρ	Density	kg/m^3
σ	Microscopic cross section	m^2
Γ	Resonance width	m