

MODULAR HELIUM REACTOR FUEL CYCLE CONCEPTS AND SUSTAINABILITY

Chris Ellis, Alan Baxter, Arkal Shenoy

(General Atomics, P.O. Box 85608, San Diego, CA 92186, United States of America)

ABSTRACT: General Atomics (GA) has over 35 years experience in prismatic block High-Temperature Gas Reactor (HTGR) technology design. During this period, the design has recently evolved into a Modular Helium Reactor (MHR) design, and several fuel cycle studies have been performed to demonstrate its versatility. This versatility is directly related to refractory TRISO coated-particle fuel that can contain any type of fuel. This paper summarizes GA's fuel cycle studies individually, and compares each based upon its cycle sustainability, proliferation-resistance capabilities, and other performance data against Pressurized Water Reactor (PWR) fuel cycle data. Fuel cycle studies will be categorized into five cycle options: commercial LEU-NU; commercial HEU-Th; commercial LEU-Th; weapons-grade plutonium consumption; and burning of LWR waste including plutonium and minor actinides in the MHR. Results show that all commercial MHR options, with the exception of HEU-Th, are more sustainable than a PWR fuel cycle, with LEU-NU being the most sustainable commercial option. In addition, all commercial MHR options outperform the PWR with regard to its proliferation-resistance, with thorium fuel cycles having the best proliferation-resistance characteristics.

KEY WORDS: MHR; sustainability; non-proliferation

0. INTRODUCTION

From a nuclear fuel cycle perspective, the concept of sustainability has historically relied on four main issues associated with its technology: economics; safety; wastes, and proliferation [1]. A full sustainability evaluation for all of GA's proposed nuclear fuel cycle options is beyond the scope of this paper. Instead, this paper intends to summarize and compare general fuel cycle characteristics of selected MHR fuel cycles with PWR characteristics, and to provide a simplistic method for measuring both the sustainability and proliferation-resistance performance for each of the fuel cycles. The selected MHR fuel cycles evaluated by General Atomics is limited to five - commercial LEU-NU, commercial HEU-Th, commercial LEU-Th, weapons-grade plutonium consumption, and Deep-Burn options.

1. MHR APPLICATIONS

GA has been developing high-temperature, helium-cooled nuclear reactors since the middle 1960s for electricity production and a variety of process-heat applications. In more recent years, GA has been developing the passively safe, modular-sized design referred to as the Modular Helium Reactor (MHR). The MHR can be designed to operate at thermal power level up to 600 MWt with a core-outlet helium temperature in the range of 850°C to 1000°C. For this design, the possibility of a core meltdown is precluded through the use of refractory, TRISO coated-particle fuel and nuclear-grade graphite fuel elements with high heat capacity and thermal conductivity, combined with operation at a relatively low power density with an annular-core arrangement. MHR technology is an advanced design of gas-cooled reactors to provide very high safety, high thermal efficiency and environmental advantages. This technology may be applied in several design applications including production of electricity, hydrogen, and process heat generation.

The GT-MHR module (see figure 1) couples a gas-cooled MHR, contained in one vessel, with a high efficiency Brayton cycle gas turbine (GT) energy conversion system contained in an adjacent vessel. The reactor and power conversion vessels are interconnected with a short cross-vessel and are located in a below grade concrete silo. This type of MHR application can incorporate a variety of fuel cycles, and is the only application considered within this paper.

For a promising alternative source for producing hydrogen, process heat from an MHR can drive a set of chemical reactions that splits water into hydrogen and oxygen. Preliminary evaluations have shown the sulfur-iodide (SI) process can produce hydrogen with high efficiency when driven by 850°C to 950°C process heat from an MHR [2]. Preliminary economic assessments have shown an MHR-driven SI plant can be cost competitive with a steam-reforming plant, especially if the cost of natural gas increases due to increased demand. This type of application is called the H2-MHR (see figure 1.)

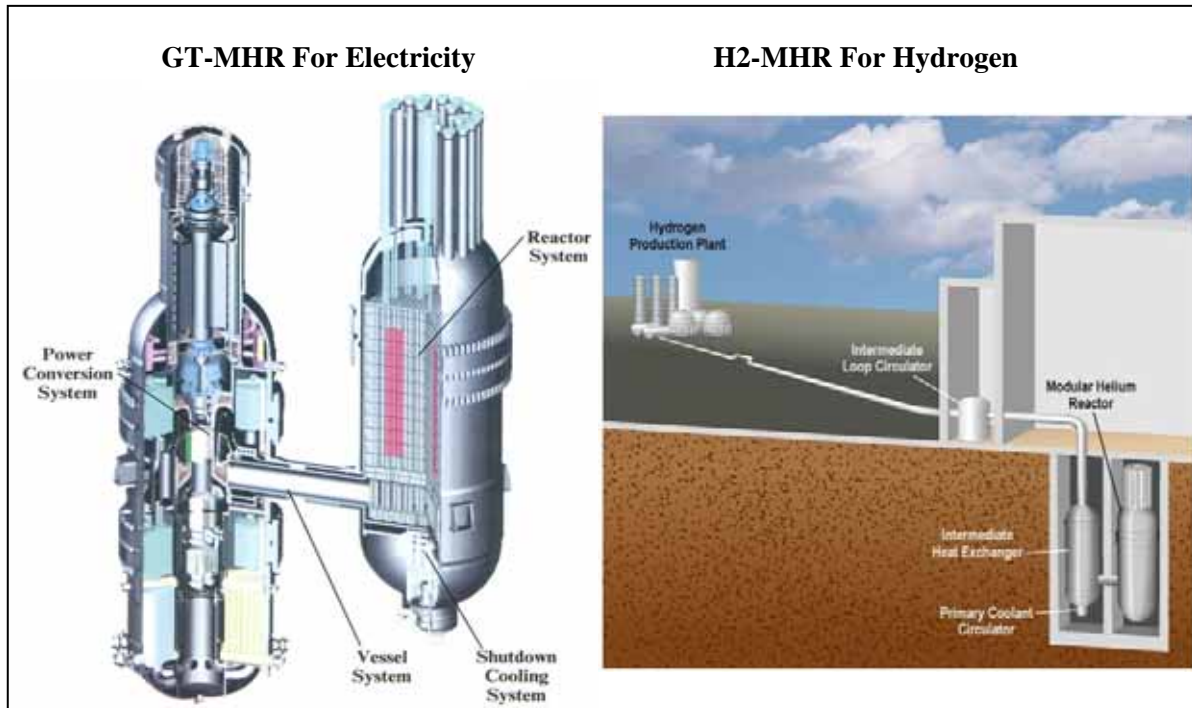


FIGURE 1. MHR Applications.

2. SUMMARY OF GT-MHR FUEL CYCLE STUDIES

Inherent in the characteristics of GT-MHR core design is its capability for utilizing various fuel cycle types. The following sub-sections detail the five fuel cycle options that were studied for this paper. The commercial options are designed solely for energy applications while the remaining two are designed for efficiently burning specified nuclides.

2. 1. COMMERCIAL LEU-NU OPTION

A Commercialization option of the GT-MHR has been in development at GA since 1993 to produce electricity at competitive generation costs, and is a promising candidate for near term commercial deployment in the United States. Two different types of fuel TRISO particles are used for power profiling purposes - 19.9% low-enriched (LEU) particles and natural uranium (NU) particles. The current design uses a once-through fuel cycle, refueling half of the core at every reload interval.

2. 2. COMMERCIAL HEU-TH OPTION

This option is based upon Fort St. Vrain type fuel, which operated from 1976 through 1989. Fuel composition consists again of two separate TRISO particles, 93% high-enriched uranium (HEU) particles and fertile Th-232 particles to achieve maximum U-233 conversion ratios and therefore limit

the amount of plutonium produced. Although HEU-fueled reactors would not be considered for commercial use in the United States, the interest here is historical in nature. This design also uses a once-through fuel cycle, refueling half of the core at every reload interval.

2. 3. COMMERCIAL LEU-TH OPTION

The fuel cycle concept was initially conceived at GA in 1977 and promoted as a “non-proliferation” design option since both fissile and fertile fuels will co-exist in the same TRISO fuel particle. This design effectively denatures the U-233 produced from the fertile Th-232 fuel by mixing it with non-fissile plutonium nuclides generated from the 19.9% LEU. A significant quantity of Pu-238 is also produced so that the plutonium would also generate a considerable amount of decay heat, thereby making the depleted fuel less attractive as bomb material. This design would also use a once-through fuel cycle, refueling half of the core at every reload interval.

2. 4. PLUTONIUM CONSUMPTION OPTION

When fueled with weapons-grade plutonium (94% enriched Pu-239), the GT-MHR can provide the capability to consume more than 90% of the initially charged PU-239, and more than 65% of the initially charged total plutonium, in a single pass through the reactor. This option is referred to as a Plutonium Consumption MHR (PC-MHR), and is currently under development in a joint United States – Russian Federation program to provide capacity for disposition of surplus weapons plutonium. The current design is also a once-through fuel cycle type, however only a third of the core is replaced during refueling.

2. 5. DEEP-BURN OPTION

The Deep-Burn option of the MHR (DB-MHR) has been proposed by GA to fit nuclear sustainability objectives [3]. It uses transuranic (TRU) waste discharged from LWR as fuel. This waste is then destroyed by fission, and capture-followed-by-fission, while producing useful energy at high efficiency. The DB-MHR contains two different kinds of TRISO fuel particles - a Driver Fuel (DF), consisting of plutonium and neptunium, mainly composed of fissionable materials (Pu-239 and Pu-241), and a Transmutation Fuel (TF), consisting of the other Minor Actinides (MAs) plus the transuranics left in the DF after a complete irradiation cycle. One additional reprocessing step after the extraction of the TRU waste from the LWR discharge is required in this cycle, and other options that eliminate this second reprocessing step are being evaluated.

3. COMPUTATIONAL METHODS

For the commercial fuel cycle options, cross section sets were generated using GA's in-house MICROX [4] code. MICROX is an integral transport theory flux spectrum code, which solves the thermalization and neutron slowing down equations on a detailed energy grid for a two-region lattice cell. Fluxes in these two regions are coupled by collision probabilities based upon a flat flux approximation. MICROX accepts the fuel region to have grain structures in both the thermal and fast energy ranges. Required input into MICROX includes basic nuclear data from two binary files, which consist of 99 fast energy groups, 101 thermal energy groups, and Doppler-broadened cross section data. Although its nuclear database is considered old, MICROX has been validated against gas-cooled reactor benchmarks [5].

There is a noticeable change in neutron energy spectra due to high plutonium burnup in the PC-MHR fuel cycle option. As a result, cross sections and concentration-dependent self-shielding factors for this option were generated using GA's in-house MICROBURN [6] code. MICROBURN is a spectrum-burnup code, which combines the two-region spectrum code MICROX with the burnup subroutines from GA's in-house one-dimensional diffusion-burnup code FEVER. The code calculates the time-dependent spectrum in detail for a doubly heterogeneous lattice cell, i.e., a two-region cell consisting of rod and moderator with grain structure in the rod.

MONTEBURNS [7] is an automated, multi-step Monte Carlo burnup code system, which combines the general-purpose, continuous-energy, Monte Carlo transport code MCNP [8] with the isotope generation and depletion code ORIGEN2 [9]. The MONTEBURNS model utilizes pointwise cross section data directly and provides a straightforward model for the DB-MHR option, which can be accommodated in a reasonable time frame in today's high speed computers. Therefore, all

calculations for the DB-MHR option in this paper were performed with MONTEBURNS.

Depletion calculations were then performed using GA's in-house GARGOYLE [10] code for both the commercial and PC-MHR fuel cycle options. GARGOYLE is a zero-dimensional, multigroup depletion code that is capable of performing searches on nuclide loadings and cycle lengths during approach to the equilibrium fuel cycle, using broad-group nuclide cross section sets generated from MICROX or MICROBURN. The code is also capable of performing accurate decay heating calculations. All commercial-type fuel cycles are based upon an eighteen-month cycle length at 87% capacity factor, leading to a commercial fuel cycle length of 476 effective full power days (EFPD) and a fuel residence time of 953 EFPD for their two-segment cores. Both the PC-MHR and DB-MHR are special types of fuel cycles, not designed to conform to the commercial's eighteen-month cycle length. The PC-MHR is designed to operate at a fuel cycle length of 260 EFPD, leading to a fuel residence time of 780 EFPD for its three-segment core. For a best estimate of comparing non-proliferation performance, an exception was made for this paper on the PC-MHR option to increase its cycle length by 58 EFPD to achieve a similar commercial 953 EFPD fuel residence time.

The sustainability of a given fuel cycle was estimated to have units of MWe-year per metric tonne of uranium ore and/or metric tonne of Th-232, and was only measured for the commercial fuel cycle options. Both the PC-MHR and DB-MHR fuel cycles may not be viewed as sustainable, since their fuel resources do not directly depend upon a natural resource. A Non-Proliferation Index [11] was estimated for all fuel cycle options based upon its discharge composition. The Index was calculated from the sum of the following three parameters:

$$\text{Bare Critical Mass (BCM) of Discharged Fuel (kg)} = \text{PU}_1(\text{A}_1) + \text{PU}_2(\text{A}_2) + \text{PU}_3(\text{A}_3) + \text{PU}_4(\text{A}_4) + \text{PU}_5(\text{A}_5)$$

$$\text{BCM Decay Heat (W/BCM)} = \text{PU}_1(\text{B}_1) + \text{PU}_2(\text{B}_2) + \text{PU}_3(\text{B}_3) + \text{PU}_4(\text{B}_4) + \text{PU}_5(\text{B}_5)$$

$$\text{Spontaneous Fission Neutrons of BCM (n/BCM-s)} = \text{PU}_1(\text{C}_1) + \text{PU}_2(\text{C}_2) + \text{PU}_3(\text{C}_3) + \text{PU}_4(\text{C}_4) + \text{PU}_5(\text{C}_5)$$

where,

PU_x = Weight fraction of nuclide x in total discharged plutonium,

A_x = BCM (kg, α -phase) of nuclide x,

B_x = Decay heat (W/kg) of nuclide x,

C_x = Spontaneous fission neutrons (n/g-s) of nuclide x,

nuclides 1, 2, 3, 4, and 5 refer to Pu-238, Pu-239, Pu-240, Pu-241, and Pu-242, respectively.

Higher values of this Non-Proliferation Index would indicate that the discharged fuel is less likely to be weapons useful. To make consistent comparisons of this Index, it's important to have similar fuel residence times since the relative abundance of the plutonium nuclides within the fuel discharge is highly dependent upon burnup.

4. FUEL CYCLE DATA COMPARISON

To put the performances of the GT-MHR fuel cycle options into perspective, we compared their basic equilibrium operation data with the parameters of the PWR [12] operated with uranium fuel. Table 1 compares several key fuel cycle parameters.

The absolute values of the Non-Proliferation Indices become more useful if each of the three parameters were normalized to the Index of typical weapons-grade plutonium, then summed together, as shown in figure 2. It can be seen from this figure that all MHR fuel cycles have excellent performance from a non-proliferation standpoint as compared to the PWR. For non-commercial fuel cycle options, both also outperform the PWR, with the DB-MHR Non-Proliferation Index of 82 far exceeding the PC-MHR Index of 23. HEU-TH has such a high Index due to its discharge having a substantial percentage of PU-238 (produced from thorium), which has the highest decay heat of all the plutonium nuclides. An additional performance measure for the commercial type fuel cycle options is shown in figure 3, which plots the Non-Proliferation Index versus the Sustainability Index for each cycle. From this standpoint the LEU-NU fuel cycle is the best.

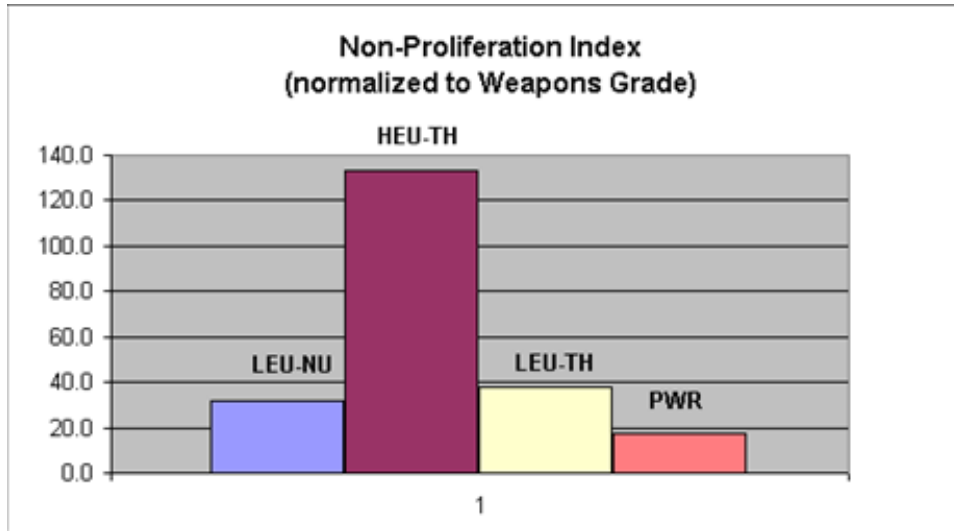


FIGURE. 2. Non-Proliferation Index of Modular Helium Reactors compared to PWR

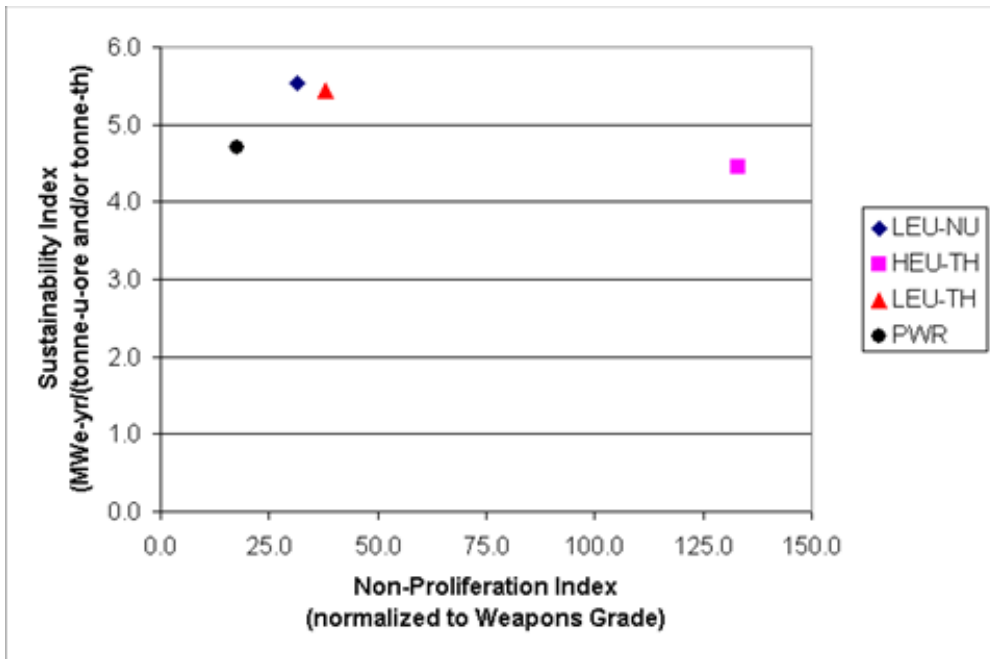


FIGURE. 3. Non-Proliferation vs. Sustainability

TABLE 1. Fuel Cycle Parameters

Reactor Rating	LEU-NU	HEU-Th	LEU-Th	PC-MHR	DB-MHR	PWR
Reactor Thermal Power (MWt)	600	600	600	600	600	3000
Number of Power Module/Plant	4	4	4	4	4	1
Plant Thermal Power (MWt)	2400	2400	2400	2400	2400	3000
Net Thermal Efficiency (%)	47.7	47.7	47.7	47.7	47.7	33.0
Plant Electrical Power (MWe)	1145	1145	1145	1145	1145	990
GWe - Yrs (60 Yrs @ 87% CF)	59.8	59.8	59.8	59.8	59.8	51.7
Thermal Discharge	LEU-NU	HEU-h	LEU-Th	PC-MHR	DB-MHR	PWR
Heat Rejection (GWt/GWe)	1.1	1.1	1.1	1.1	1.1	1.8
Cooling Requirements (10 ⁴ Acre-Ft/Gwe-Yr)	1.4	1.4	1.4	1.4	1.4	2.4
Equilibrium Fuel Cycle per Module	LEU-NU	HEU-Th	LEU-Th	PC-MHR	DB-MHR	PWR
HM Loading (tonnes/GWt)	7.5	7.8	11.6	1.8	2.8	35.9
Fissile Particle Enrichment (%)	19.9	93.0	19.9	94.0	65.2	-
Core Average U-235 Enrichment (%)	15.5	17.9	10.0	-	-	4.2
SWU Demand (10 ³ kg-SWU/GWe-Yr) @ .2% Tails	208	285	212	-	-	190
Burnup (GWt-Day/ITHM) / (Gwe-Day/ITHM)	126/60	122/58	82/39	517/247	2542/1213	41/13
U ₃ O ₈ Consumption (tonnes/GWe-Yr) @ .2% Tails	182	220	179	-	-	212
ThO ₂ Consumption (tonnes/GWe-Yr)	-	5.1	4.6	-	-	-
Core Average FIMA (%)	13.4	12.9	8.8	55.3	67	4.7
Spent Fuel Discharge at Equilibrium per Module	LEU-NU	HEU-Th	LEU-Th	PC-MHR	DB-MHR	PWR
Volume, Elements / Fuel (ft ³ /GWe-Yr)	4291/874	4291/874	4291/874	4290/833	4290/833	348/84
Discharged HM (tones/GWe-Yr)	5.3	5.5	8.8	0.7	0.1	26.0
Fissile Particle Enrichment / Average Enrichment (%)	5.6/4.2	57.4/57.6	-/2.5	-	-	-
Total PU Fraction in HM (%)	1.8	0.2	0.1	97.2	78.1	1.3
Discharged PU (kg/GWe-Yr)	96	9	10	653	426	338
PU-239 Fraction (%) (PU ²³⁹ /Total HM)	0.7	0.0	0.0	39.6	5.3	0.7
Discharged PU ²³⁹ (kg/GWe-Yr)	36.1	1.9	2.9	266.5	29.0	187
Heat Load @ 10 Yr (KWt/GWe-Yr)	24.0	24.9	13.8	29.8	180	26.5
Heat Load @ 100 Yr (KWt/GWe-Yr)	5.0	5.8	0.9	19.1	27	16.2
Heat Load @ 1000 Yr (KWt/GWe-Yr)	0.8	0.1	0.2	4.9	0.5	5.1
Heat Load @ 10000 Yr (KWt/GWe-Yr)	0.1	0.0	0.0	0.5	0.2	1.3

5. CONCLUSIONS

Table 1 shows several advantages of the commercial fuel cycle options over the PWR design. In particular the commercial MHR options, with the exception of HEU-Th, offer much greater electricity production per unit of U_3O_8 consumed because of their higher conversion efficiency, and make greater use of the fuel due to their higher burnup capability. They also have a much lower actinide loading in the discharged waste fuel, which also has much greater proliferation resistance. The initial heat load of the spent fuel is also consistently lower in the commercial options. The HEU-Th option, employed in the Fort St. Vrain reactor, uses fully enriched uranium as the fissile material, which requires a large amount of U_3O_8 and results in its low sustainability index. As expected, the LEU-Th option performed very well in the non-proliferation area (see figure 2.) This was primarily due to a high percentage of Pu-242 in the plutonium discharge, which has a large BCM and a high rate of spontaneous fission neutrons. For the sustainability estimate, the LEU-NU option outperformed the remaining commercial options (see figure 3), although this highly depends upon equilibrium fuel loadings and could be further optimized. The PWR does have less of a SWU demand, but again this is offset by high MHR burnup capability.

The PC-MHR and DB-MHR options both have the highest burnup, highest decay heat load, and lowest equilibrium fuel loading of all the other fuel cycles. The DB-MHR outperforms the PWR in terms of Non-Proliferation Index, however there is a large difference between the PC-MHR and DB-MHR Indices. This is due to the DB-MHR discharge having the most optimal plutonium nuclide distributions, specifically high weight percentages of PU-238 and PU-242 and low weight percentages of PU-239.

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AUTHOR INTRODUCTION

Chris Ellis is a staff engineer at General Atomics. He acts as a nuclear engineer in the area of GT-MHR technology. He received both his Bachelor of Science degree in 1998 and his Masters degree in 2000 from Oregon State University. (chris.ellis@gat.com)

Alan Baxter is manager of nuclear engineering in the Electronuclear Systems group at General Atomics. He received his Bachelor of Science degree from the University of Toronto (Canada) in 1959, and his Ph.D. in Nuclear Engineering from the University of Illinois (USA) in 1964. (Alan.Baxter@gat.com)