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The Uranium Enrichment Industry and the SILEX Process

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SUMMARY Silex Systems Limited has been developing a new laser isotope separation process since 1992. The principle application of the SILEX Technology is Uranium Enrichment, the key step in the production of fuel for nuclear power plants. The Uranium Enrichment industry, today worth ~ US$3.5 Billion p.a., is dominated by four major players, the largest being USEC with almost 40% of the market. In 1996, an agreement was signed between Silex and USEC to develop SILEX Technology for potential application to Uranium Enrichment. The SILEX process is a low cost, energy efficient scheme which may provide significant commercial advantage over current technology and competing laser processes. Silex is also investigating possible application to the enrichment of Silicon, Carbon and other materials. Significant markets may develop for such materials, particularly in the semiconductor industry.

1. BACKGROUND TO SILEX SYSTEMS LTD

Silex Systems Limited (Silex) was established in 1988 (by Dr. M. Goldsworthy) as the research subsidiary of Sonic Healthcare Limited (Sonic), an Australian publicly listed company. Silex has been developing its unique, laser based, isotope separation technology known as SILEX (Separation of Isotopes by Laser EXcitation) since 1992.

The company is currently pursuing the following commercial applications of SILEX Technology:

- Uranium Enrichment – for the civilian Nuclear Fuel Cycle. Current market value is approximately US$3.5 Billion pa.
- Silicon Enrichment - for potential application in the semiconductor wafer industry (production of Si-28 wafers).
- Carbon Enrichment – for potential application in the semiconductor (heatsink) industry (C-12) and the medical diagnostics industry (C-13).

Silex was divested from Sonic through a distribution in specie in February 1996, and immediately set out to form a strategic alliance with an industry partner.

In November 1996, a Licence and Development Agreement for the application of SILEX Technology to uranium enrichment was signed with the United States Enrichment Corporation (USEC), the largest supplier of enrichment services in the world. Formerly part of the US Department of Energy, USEC was privatised through a listing on the New York Stock Exchange in July 1998. The privatisation was the largest in the US in the last 10 years and USEC is now capitalised at approximately US$1.2 Billion, with annual revenues of approximately US$1.4 Billion p.a.

Silex listed on the Australian Stock Exchange on 7th May 1998, and currently (Sept '99) has a market capitalisation of approximately $400M, with over 4000 shareholders. Subject to the continued successful development of the company's technology, Silex intends to consider a future listing on either the NASDAQ or NYSE exchange in the US.

In November 1998, the company commenced a Feasibility Study on the application of SILEX Technology to Silicon and Carbon enrichment, for potential use in the Semiconductor Industry. This is being conducted in conjunction with Isonics Corporation, an advanced materials company in the US, and SDI Pty Ltd, a South African technology company.

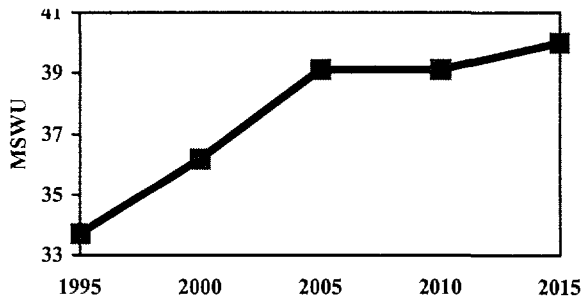
2. THE URANIUM ENRICHMENT INDUSTRY

The main focus of the Company's current activities is on the Uranium Enrichment application through the Agreement with USEC. Uranium Enrichment is the key step in the production of fuel for the global Nuclear Power industry, which currently provides approximately 18% of the world's electricity, a figure which is likely to increase with continuing economic development in Asia and the growing environmental problems associated with the use of fossil fuels.

Enrichment is a technically difficult process, which constitutes a major component of nuclear fuel costs (approximately 30% of the total fixed costs). Enrichment involves increasing the concentration of the 'active' U-235 isotope from 0.7% to approximately 3% - 5%. The work required to perform enrichment is measured in *Separative Work Units (SWUs).*

The world-wide uranium enrichment market is currently worth nearly US$3.5 billion p.a., constituting an annual demand of approximately 35 million SWUs. Current and projected enrichment demand for the period 1995 to 2015 is shown in Figure 1. The steady increase in estimated demand to 40 MSWU in 2015 assumes little growth in the nuclear industry. The only expanding market is in Asia, but this is to some extent negated by continuing plant shutdowns in other markets.

Figure 1: Current & Projected Enrichment Demand 1995 - 2015



3. CURRENT ENRICHMENT TECHNOLOGIES

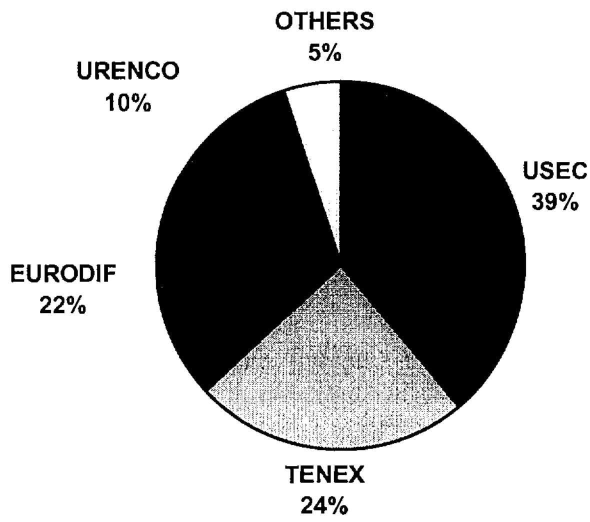
Two technologies, gaseous diffusion and gas centrifuge, are currently used to enrich uranium for nuclear electricity plants. Both use UF_6 as the chemical form of uranium for feedstock, primarily because UF_6 is gaseous at room temperature but becomes solid under moderate pressure. As a result, UF_6 is readily and safely transported in large quantities in steel cylinders. Both processes rely on the small mass difference between the U-235 and U-238 Isotopes to achieve separation, either by *diffusion* through a semi porous membrane or by *centrifugation* (spinning) at high speed.

More than half of current demand for enrichment services is supplied by three gas diffusion plants, two in the United States (operated by USEC) which are 45 years old and one in France (operated by Eurodif) which is 20 years old. Over one third of current demand for enrichment services is supplied by gas centrifuge Technology located in Europe (Urenco), Russia (Tenex) and Japan (JNFL).

Some proportion of USEC's market may be satisfied by highly enriched uranium (HEU) derived from the Megatons to Megawatts Agreement, under which HEU from weapons dismantling is being blended down to levels which are directly useable for power station fuel. Figure 2 shows approximate world enrichment market shares for 1998.

Total operating costs for centrifuge SWU are around one tenth of diffusion. However, the high capital costs of establishing a centrifuge plant and the fact that the existing diffusion plants have excess capacity relative to current demand, have resulted in the slow development of centrifuge capacity.

Figure 2: Approximate Enrichment Market Shares -1998



4. NEW ENRICHMENT TECHNOLOGIES

Industry participants, in particular the US Government, have invested heavily over the last three decades searching for a new enrichment technology which will not only replace diffusion, but will also be significantly more economic. The processes currently expected to replace the diffusion enrichment plants are advanced centrifuge technology developed by Urenco, and laser-based technologies.

USEC, which operates the US diffusion plants, had been developing a technology known as AVLIS (**A**tomic **V**apour **L**aser **I**sotope **S**eparation), which it took control of from the US Department of Energy upon privatisation. AVLIS was for many years the front-running laser technology.

However, in June 1999, USEC shutdown the AVLIS Development Program, citing poor economic prospects as the driving issue. USEC intends to continue with its evaluation of the SILEX Technology to determine whether it has sufficient economics and reliability to be deployed as its future enrichment technology. It will also continue an evaluation of the gas centrifuge option.

The laser-based processes currently being developed around the world are described briefly below.

AVLIS The United States Government is estimated to have invested more than US$2.0 billion since the late-1960's on the development of AVLIS. Development continued at the Lawrence Livermore Laboratories in California under USEC's sponsorship post privatisation, until it was shutdown recently. A process similar to AVLIS called SILVA is still being developed by a French Government agency, but this effort is also understood to be winding down.

MLIS (**M**olecular **L**aser **I**sotope **S**eparation). This UF_6-based process has been the subject of well funded development projects in several countries since the early 1970's, including Germany, Britain, USA, Japan and South Africa (in conjunction with the French). All of these efforts have since been disbanded, except for a small continuing project in Japan, which also appears to be in decline.

SILEX This laser based process was invented by Silex and is currently under development in conjunction with USEC. Since the shutdown of AVLIS, SILEX is the only laser based technology being pursued by USEC for possible future replacement of its diffusion plants.

5. FEATURES OF THE SILEX PROCESS

The SILEX Process and engineering concept represents a new approach to laser enrichment of uranium. The intrinsic qualities of SILEX are found in novel techniques and innovative use of relatively simple engineering concepts, which are based on well established principles and technologies. The main features and advantages of the SILEX proposal, which set it apart from other laser enrichment schemes, can be summarised thus:

- SILEX is a very low energy process.
- SILEX utilises the current industry feedstock- UF_6, making industrial integration simple.
- SILEX is based on relatively simple and practical separation modules.
- SILEX is a modular technology providing versatility in deployment.
- Innovative engineering designs allow truly continuous operation with SILEX.
- SILEX is expected to have low overall power consumption and capital costs.

6. THE USEC AGREEMENT

An agreement was reached with USEC in late 1996, under which an exclusive licence to use the technology for uranium enrichment was granted. In return, the Agreement sets out the conditions under which USEC funds the development program and pays milestone payments and royalties. The main commercial terms of the Agreement are as follows:

- A US$7.5M fee for exclusive rights to uranium enrichment was paid by USEC to Silex in November, 1996.

- USEC continues to fund the entire development program, including the cost of the Pilot Module and Pilot Plant programs, and patent protection.

- Three milestone payments totalling US$18M are to be paid over the next three to four years provided technical targets are met.

- US$15M in fees (3 x $5M pa) will be paid to Silex during construction of a commercial plant assuming USEC ultimately decides to commercialise SILEX.

- A royalty of 5% - 8.75% of gross revenue derived from the technology will be paid to Silex. (The rate varies depending on the relativity between costs and revenues.) If all revenues are derived from SILEX the annual royalty could be as high as US$130M pa.

In order to facilitate the joint Silex-USEC development of SILEX Technology, a new Australia-US Bi-lateral Treaty for Nuclear Cooperation had to be negotiated and enacted. The Treaty drafting and negotiations took almost 2 years to complete. Whilst the approval process has since been completed by the Australian Government, it has taken a little longer in Washington. However, at the time of writing this report, the Secretary of Energy and the Secretary of State had signed off, and signature by President Clinton was imminent. The Treaty is therefore set to come into effect in early 2000, enabling the full technology transfer process to proceed thereafter.

7. THE SILEX DEVELOPMENT PROGRAM

The SILEX Process was initially proven to "work in principle" on a laboratory scale for Uranium in 1994. In the subsequent Pilot Module Program (being completed at the time of this report), the scalability and preliminary economics of the technology have been investigated. USEC will assess the results of this Program in its sole discretion. If they are satisfactory, USEC will formally proceed to the next program (the Pilot Engineering Study), and the first half of the 'First Milestone' payment (US$2.5M) will be made to Silex. The second US$2.5M payment will be made when the Bi-lateral Treaty comes into effect (early 2000). An outline of the future development program is given in the table below:

Program Stage	Earliest Completion	Milestone Payment
Engineering study	Mid 2001	US$ 3M
Pilot Plant Program	End 2003	US$10M
Commercial Deployment	End 2007	Royalties

8. OTHER POTENTIAL APPLICATIONS OF SILEX TECHNOLOGY

The SILEX core technology has other potential applications which may prove to be commercially viable. These will be pursued actively over the next few years and include:

8.1 Semiconductor Materials

Semiconductors, which are integral to all computer and electronic systems, are generally made from Silicon (Si). Today's computer chips and electronic devices are reaching the limits of performance, dictated by technical barriers inherent in natural Silicon material, principally heat build up. In recent years increasing interest has been shown in semiconductors which have been made from isotopically enriched Silicon. The use of isotopically enriched Silicon has been shown to offer technical advantages in two areas:

- Increased thermal conductivity (ie, better heat dissipation). Recent published results verify increases of up to 60% in the thermal conductivity of enriched Silicon-28. In a typical computer chip, this may translate to a drop in operating temperature of 30~40°C – potentially providing improved semiconductor performance.

- Significant improvements in advanced semiconductor production via Neutron Transmutation Doping (NTD). The NTD method is used to make sophisticated, high power silicon based semiconductor devices.

Several research and commercial organisations around the world have been investigating these phenomena for a number of years, but without consideration of an economic source of enriched material. To date, no economically viable source of enriched Silicon has emerged. The SILEX Process may be able to provide this source for the first time.

Synthetic diamond heat spreaders and heat sinks, made today from natural carbon, are also used extensively in the semiconductor industry. Published research results show that synthetic diamond made from enriched carbon (> 99.9% C-12) also exhibits significantly improved thermal conductivity. The potential for SILEX Technology to produce enriched C-12 is also being investigated. The 'by-product' from this application (Carbon-13) is already used extensively in bio-medical applications, and could therefore add value to a SILEX carbon isotope separation venture if successfully undertaken.

8.2 Nuclear Engineering Materials

Special materials are used in the construction and operation of commercial nuclear reactors, and in nuclear fuel assemblies. These materials exhibit particular properties when in the presence of neutrons (ie in the reactor). Such properties are utilised to enhance reactor performance resulting in cost reductions for electricity generation. The properties of several of these materials, including Boron (B), Zirconium (Zr), Zinc (Zn) and Gadolinium (Gd), can be significantly improved if enriched. The SILEX Process, with its potential for inherently low enrichment costs, may provide a commercially superior route for the production of some of these materials.

8.3 Medical Isotopes

The medical isotopes of primary commercial interest are Carbon-13, Molybdenum (for Technetium production), Xenon, Palladium, Thallium and Zinc (for Gallium production). These isotopes form the basic materials used for bio-medical and in-vivo diagnostic procedures, including detection of cancer and organ disease. Whilst the technical advantages of using enriched materials for medical radioisotope production are reasonably well understood, further studies are required to establish the associated economics and the size of potential markets.