



ANALYTICAL CONTINUOUS FLOW SYSTEMS. WHERE TWO WORLDS
COLLIDE! FROM GRAVIMETRY AND TEST TUBES TO FLOW SYSTEMS
TO FIA TO SIA TO PAT
AND FROM ORSAT TO CONTROL ROOM TO PAT TO TAP

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Manual analysis plays a dominant role in most of the Analytical World from the 17th century up to most of the 19th century, dominantly used in the 1940-1970 and even later into the 20th century. Therefore the first part of the talk will start with “weighing” analysis in the AlChem era around 1350 BC, followed shortly by flow analysis with chromatography starting in 1905, some non-segmented inventions in 1911 and the road of Leonard T. Skeggs in the early 1950 to the AUTOANALYSER era in the 1960’s. FIA started with Jarda Ruzicka and Elo Hansen in the mid seventies on LEGOs. The first practical FIA for the water authorities was soon after built in the Chemistry Department at UP in South Africa, followed by various different configurations up to the first process analyzer. A normal ink pen led to the first concept of SIA in Pretoria followed by the collaboration with CPAC and Jarda Ruzicka at the University of Washington, USA with Graham Marshall as PhD student who completed his PhD at the University of Pretoria in the early nineties. This was followed by numerous developments of process analyzers leading eventually to the PAT concept from the continuous flow viewpoint. This is road one in the analytical world. I started my career at SASOL with manual analysis in a routine laboratory, where I also came in contact using the ORSAT gas analyzer that was patented before 1873 by Mr. H Orsat. Various instruments play a dominant role in gas analysis in the 1970-1980, with GC most of the time the front runner. In the 1980s and early 1990s, various aspects of automated non-destructive spectroscopy and the first version of scanning spectroscopy was introduced by the Chemistry Department in Pretoria leading to the first PAT type configurations with chemometrics and the second road crossing road one. These types of innovations were followed by some initial work in TAP that culminated currently to the modern technology with TAP technology in gas systems. The talk highlighted various innovation aspects from chromatography, flow systems, FIA, SIA, PAC and PAT to Real-time Integrated Industrial Monitoring and Control Information Management Systems and eventually to the temporal analysis of products (TAP) concept with the latest TAP concept and a future vision of invasive and non-invasive non-destructive real-time integrated multi-analyte fully automated interactive process analyzers as incentives and new paradigm concepts of innovative, low cost, easy to operate, portable sensing platforms with an interrogative kinetics approach for fast, transient measurements and a high time resolution in industrial processes.

INTRODUCTION AND THE BACKGROUND, THE BEGINNING

Retrieval of data revealed that manual analysis plays a dominant role worldwide from the 17th century up to most of the 19th century and strange also forms part of the early 20th century. “Weighing” analysis or a rough form of direct “gravimetric” analysis was probably performed around 1350 BC when the Babylonians start to use fire assay to test the purity of gold by comparing the “weight” before and after fire assay. Gravimetry is among the most accurate analytical techniques and gravimetric determinations form for a long period part of chemical analysis as a basic reference standard method, but although it was part of most analytical university practical courses during the 19th century,¹⁻⁵ the technique lost its place in Analytical Chemical assays due to the tedious and time consuming procedures that are followed. Mohr’s argentometric method of determination of chlorides (published by Karl Friedrich Mohr in 1856) by titration of silver nitrate is one of the oldest titration methods still in use. It is a very simple method. Chlorides are titrated with silver

nitrate solution in the presence of chromate anions and the end point is signalled by the appearance of red silver chromate.¹⁻⁵ Titrimetry is another analytical concept that is for a long period with us as illustrated on the cover of the thesis of a Danish historian (Fig. 1) of Analytical Chemistry.⁶ What is furthermore interesting is that the volumetric glassware and concepts of solution handling have changed very little during the last 200 years except that we are now moving to the micro scale with micropipettes.

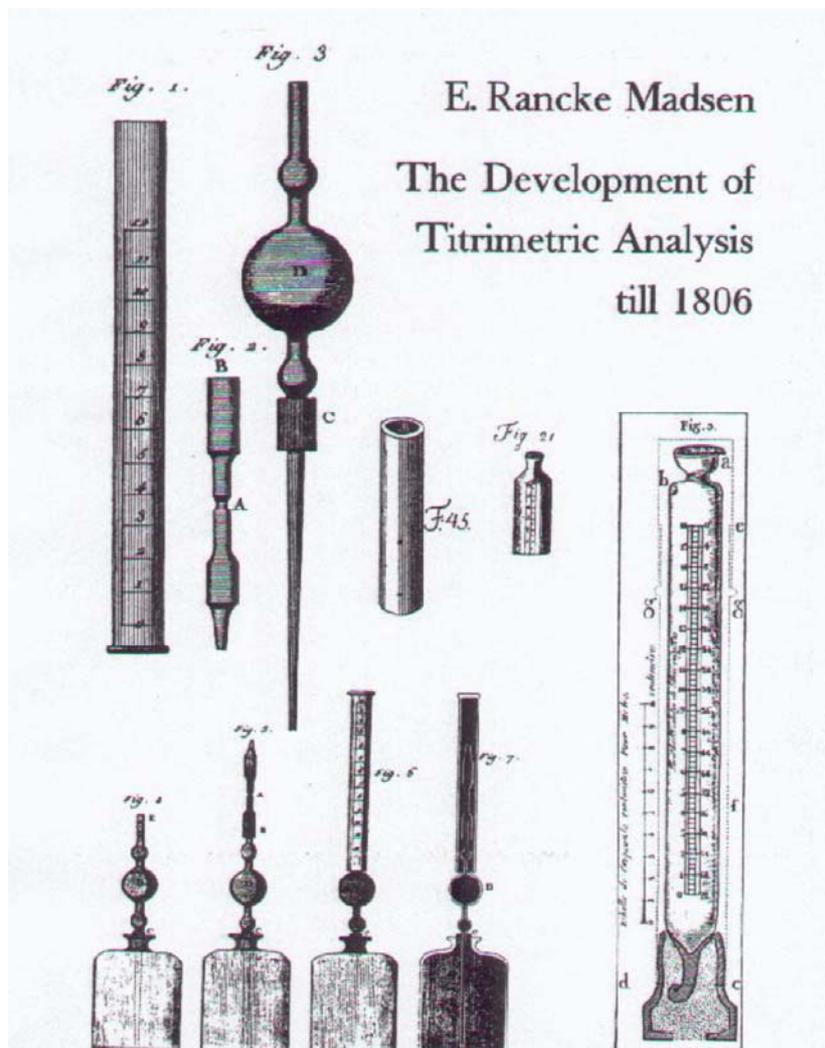


Fig. 1 – Volumetric glassware and concepts. Cover of the thesis of a Danish historian of Analytical Chemistry. Reproduced from Ref. 6.

CHROMATOGRAPHY INVENTION

The idea of flow analysis was first employed by Ramsey in 1905 with chromatography to separate mixtures of gases and vapours.^{7,8} This was followed by Mikhail Tswett in 1906 when he obtained a number of colored bands of plant pigments on a chromatographic column packed with finely divided calcium carbonate.⁹ Martin and Synge enunciated the concept of Gas-Liquid Chromatography (GLC) in 1941 in a pioneering theoretical study of theoretical plates,¹⁰ introduced GLC¹¹ and received the Nobel Prize in 1952.¹² The first Gas-Chromatography (GC) instrument appeared on the market in 1956. The sensitivity, speed, accuracy, identification, and determination of volatile compounds have resulted in a phenomenal growth in the 1960's. SASOL was one the first petroleum and petrochemical industries that installed a number of GC instruments in their special laboratory and it was estimated that around 60,000 gas chromatographs were already in use at the end of the 1960's in the world.⁷

NON-SEGMENTED FLOW SYSTEMS

Non-segmented flow systems (NSFS) were first recorded by Dr Albert Griffiths of Birkbeck College in 1911 when he measured viscosity of water at very low flow rates using a drop of fluorescein solution as marker in a carrier stream of water flowing slowly through a capillary tube.¹³ At slow flow rates radial diffusion plays the dominant role, and the colouring matter travels along the tube approximately as if the liquid moved in a solid column. Therefore with the introduction of a short length of fluorescein solution into the carrier stream in the tube, a symmetrical coloured column of slowly increasing length is obtained, the centre of which indicates the mean speed of the liquid. Sir Geoffrey Taylor studied the dispersion of an injected portion of soluble matter in water flowing through a tube¹⁴ and his theory on the effect of molecular diffusion on dispersion forms one of the basic aspects that was considered on the development of the initial theory of Flow Injection Analysis.⁶

THE AUTOANALYZER ERA

The concept of air-segmented continuous-flow analysis was pioneered by Leonard Skeggs (Fig. 2)¹⁵ in the early 1950s due to an ever increasing workload of urine and blood samples in a large clinical laboratory that could not cope anymore with tedious and time consuming manual analysis with the larger intake number of samples into the large clinical laboratory. In this origin of wet-chemistry automated analysis the main instrumental development was dedicated to liquid transport under dynamic flow conditions. His design of an automatic analyzer presented several novel features on the automatic analysis of blood for urea nitrogen, glucose, calcium, chloride, alkaline phosphatase, and acidity. In the first prototype version of an AutoAnalyzer in 1953 (Fig. 3)¹⁵ presented by Skeggs, the main unique features of the instrument in addition to the continuous peristaltic flow of samples (from an automatic disc sampler tray) and reagents from (reagent bottles), were the manifold of the system that featured a dialyzer membrane to remove suspended solids and proteins before tubing transport of liquids by a sort of peristaltic pump. An operational feature of Skeggs's air-segmented flow system was the introduction of an air segment in addition to sample and reagents where an air bubble separates each sample/reagent mixture in the liquid stream once it has been merged with it. The introduction of air causes each individual sample/reagent mixture to be divided into a number of small segments. The manifold of the instrument was further made of mixing glass coils as reactors where the different segments of samples were mixed with reagent solutions with heating or heat incubation if necessary to form reaction products of the different sample/reagent segments for photometric detection. This segmentation is retained through the succeeding stages of the analysis up to the photometer at a certain wavelength where the air is removed in a vented flow-through cell and a continuous solution phase is reformed.¹⁵⁻¹⁷ These principles of invention of Skeggs AutoAnalyzer SFA instrument have been exploited, extended and commercialized by Jack Whitehead's Technicon® Corporation in the Technicon "AutoAnalyzer" with the first commercial "AutoAnalyzer" launched in 1957 (Fig. 4)¹⁵ which dominated the continuous flow field during the sixties and the first part of the seventies.¹⁶⁻²² In the conventional Technicon AutoAnalyzer measurements are based on steady-state situations in which the physical and chemical processes in the aliquots of sample and reagent are able to reach equilibrium, resulting in steady-state signals that are more accurate and reproducible. There were also some critical remarks on the "AutoAnalyzers",²³ but the criticism could not stop the success of the Technicon "AutoAnalyzer". The first multiple analyzer was already developed by Skeggs and Hochstrasser in 1964, that led to the very successful Sequential Multiple Analyzer (SMA 12/60, 1969), an analyzer able to run 60 samples per hour for 12 analyses. In 1973 a computerized version, the Sequential Multiple Analyzer with Computer (SMAC), appeared on the market which performed 20 analyses on every sample every 20s and both these instruments together with the AutoAnalyzer II (introduced 1970) were the backbone of many routine clinical and other laboratories and the best known of Technicon's CFA instruments.^{15,19-22} Skalar, a Dutch company from Breda, was established in 1965 as a producer of analyzers for the laboratory and process industry and manufactures a range of automated chemistry analyzers i.e. for the environmental, pharmaceutical, agricultural, detergent, food and beverage laboratories with worldwide sales, support and distribution. It has since grown into a multinational organization with its own subsidiaries in most European countries and has extended the product lines to the very successful San⁺⁺ Automated Wet Chemistry Analyzer also known as the Continuous Flow Analyzer

(CFA) or also called Segmented Flow Analysis (SFA) technique where up to 16 analytical measurements can be made on a single sample simultaneously.²⁴ SEAL Analytical has over 50 years experience in environmental and industrial automated analyzers. SEAL Analytical purchased Bran+Luebbe, who earlier purchased Technicon Corporation, was the first to commercialize Continuous Flow Analysis and the QuAAtro39 AutoAnalyzer that is the very latest generation of the original world-class Technicon Continuous Segmented Flow Analyzer (SFA).²⁵



Fig. 2 – Leonard T. Skeggs Jr. Reproduced from Ref. 15.



Fig. 3 – Prototype AutoAnalyzer version in 1953. Reproduced from Ref 15.



Fig. 4 – First commercial AutoAnalyzer launched in 1957. Reproduced from Ref 15.

ORSAT, SASOL, MIMS, CAPILLARY GC, FIRST STEP TO LIMS

When SASOL (Suid-Afrikaanse Steenkool-, Olie- en Gaskorporasie, South African Coal-, Oil- and Gas-corporation) starts production in the late 1950s to the beginning of 1960s, the ORSAT gas analyzer that was patented before 1873 by Mr. H Orsat, played a very important role in the determination of CO₂, O₂ and CO content in the raw feed-gas composition to the Fischer-Tropsch reactor, especially at start-up processes. The Orsat apparatus was the only sort of semi-automated batch manual analyzer in a very large routine laboratory operating around the clock. SASOL like many other large industries in the 1950s and beyond used a traditional approach of process control with mainly off-site (off-line) analysis and with time-delay monitoring where samples from the operating system (various plant sections of SASOL) were transported to a large centralized laboratory for routine analysis.²⁶ As the number of samples from the various plants was numerous, SASOL initiated one of the first Manual Information Management Systems (MIMS) by using a recorded indexing of different samples at the entrance into the central laboratory system with distribution to various laboratory facilities, followed by routine analysis and data reporting back to the different plants. In the petroleum refinery and petrochemical industries different petroleum products ranging from gases, light petroleum products, gasoline, diesel etc. are produced from crude oil using mainly refluxing and distilling towers. Temperature (thermal probe) and pressure were main process variables and real-time monitoring was already done in the early 1960s at SASOL from large control rooms with *on-site in-line* analysis base on temperature and pressure where sampling probes penetrate the process. Commissioned in 1971, the Natref refinery (National Petroleum Refiners of South Africa) at Sasolburg had been at the cutting edge of refining technology since its inception. It was therefore no surprise that the first miniaturized analytical manifold of a flow system, as part of a gas chromatograph, was probably the production of one of the first capillary columns in the Gas Chromatography Laboratory in the early 1970's at SASOL in Sasolburg, to separate the complex hydrocarbon mixture from the Naphta Cracker at Natref. A sample splitter was used to prevent overloading of the miniaturized GC column and this was also accompanied at the same time with the first fully automated computerized system of the 38 gas chromatographs in collaboration with Siemens, Germany.²⁷ Although sampling was done manually, the further steps were fully automated as a first step to Laboratory Information Management Systems (LIMS). Various instruments play dominant rule in gas analysis in the petroleum and petrochemical industries with volatile composites in the 1970-1980 and even nowadays, with GC most of the time the front runner.

FIA AND SIA

The first generation of flow-injection analysis (FIA) was introduced in 1975 by Ruzicka and Hansen⁶ as a simple and convenient concept, which is suitable for increasing sample output in most analytical laboratories. This pioneering innovation marked an important breakthrough in unsegmented automatic continuous flow analysis and has developed over four decades as a simple, convenient, feasible analytical technique with the capability of a high sample frequency and degree of automation.^{26,28-40} Our main aim was however to develop multiple-component process analyzers and our first achievement in 1980 was the simultaneous FIA determination of sodium, potassium, magnesium and calcium in surface, ground and domestic water (Fig. 5),⁴¹ followed by the simultaneous determination of protein, phosphorus and calcium in animal feedstuffs by multi-channel flow-injection analysis.⁴² We were also very successful with our main goal in flow systems in the second half of the 1980s with the achievement of further steps towards process industrialization with the development and implementation of a fully automated on-line flow system for the manufacturing of a very important drug where the raw feed materials were non-toxic, but the intermediate products were very toxic (but inside the manifold tubes and did not come in contact with human beings) and the final curable drug product was used as medicine.⁴³ The early stages of Laboratory Information Management Systems (LIMS) in FIA from the mid-1980s up to the new millennium in 2000 were marked by time-delayed monitoring, semi-automated flow systems, but with a continuous sample feed on-line and even from in-line.⁴⁴⁻⁴⁸ A normal ink pen led to the first concept of SIA in Pretoria followed by the collaboration with CPAC and Jarda Ruzicka at the University of Washington in Seattle, USA with Graham Marshall as PhD student who completed his PhD at the University of Pretoria in the early nineties. The introduction of sequential injection analysis (SIA)^{29,34,49-52} broadened the scope of flow analysis. SIA is a technique that has

great potential for on-line measurements and process control with computer control that is essential. The system is simple and robust and convenient in the way sample manipulations can be automated, it is reliable with low frequency of maintenance and very low reagents and sample consumption.

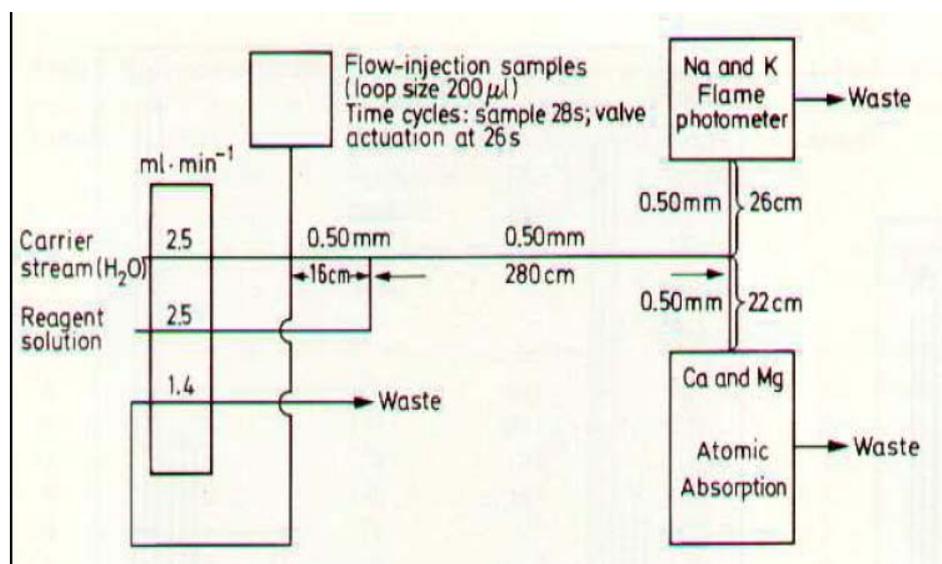


Fig. 5 – Schematic diagram of the simultaneous determination of sodium, potassium, magnesium and calcium. Reproduced from Ref 41.

REAL-TIME INTEGRATED PROCESS CONTROL, RIIMCIMS AND PAT

Our group is however further interested to move the Laboratory Information Management System (LIMS) to a better version implementing a new innovation development as Real-time Integrated Industrial Monitoring and Control Information Management Systems (RIIMCIMS) to take advantage of low cost microprocessors with wireless communication⁵³ to transform and/or upgrade the analytical and control functions in industrial processes. Our research was initially influenced by interests of an existing base of monitoring in the petrochemical industry where the initial steps and concepts of PAT was originally used in a traditional form in and around the large pipe-lines of the industrial continuous flow plant reaction (mostly organic) processes. An example is SASOL, established in 1950 in South Africa, which is still one of South Africa largest investors in technological research and development and still one of the world's largest producers of synthetic fuels.⁵⁴ Sasol's decision to proceed with the front-end engineering and design phase of an integrated, world-scale ethane cracker and downstream derivatives units and a 96 000 barrels per day gas-to-liquids (GTL) facility in the US, is the largest foreign direct investment in Louisiana, in the united state's (USA) history.^{55,56} It will be second largest plant of its kind in the world. My viewpoint on the development of Smart Process Control Analyzer Systems (SPCAS) for relevant industries (Real-time integrated process control) is that the distance between a truly representative sampling point and a detection probe and the timing between sampling and detection with final process data in process analyzer systems should be as short as possible for industries to function optimally and sustainably to deliver high-quality products using either Process Analytical Technology (PAT) or Performance Product Measurement Techniques (PPMT) or a combination of both in closed-loop process control for Total Quality Industrial Sustainable Management (TQISM). The ideal situation will be an interactive real-time sampling, detection probe inside the industrial process. Some basics in Good Industrial Process Management are the following. In any well-defined functional industry the following unit operations:- sampling, sample processing, detection, data assembling and data processing are essential tools for high-quality efficient sustainable production. Relevant industry in tact dictates the way these operational units are handled and should function properly to satisfy specific requirements. The sampling environment can range from very high temperatures (up to near 1000 °C in gas to liquid refineries) to far below freezing point (in space shuttles), from gas, liquids and solids to solutions and mixtures thereof, from simple single entities to simple complex matrices, from static difficult complex

matrices to rapid dynamic changing difficult complex matrices, from elemental to inorganic to organic substances and mixtures thereof (homogeneous or heterogeneous and mixtures thereof). What is however very important, is that timing is essential for fast and very good decisions in the whole process environment.

SULFOLIN PROCESS

In the sulfolin process in the Sasol-Lurgi gasification process vanadium in alkaline medium in the flue-gas scrubbers is used to remove hydrogen sulphide gas from sour gas streams. In the process H_2S is oxidized to elemental sulphur by vanadium (V) which is reduced to vanadium (IV). Vanadium (V) concentration should be monitored during this absorption stage in order to monitor the efficiency of the oxidation-reduction process and also to prevent overloading of the circuit by V(IV), since this leads to a loss of vanadium from the process. In the reoxidation circuit, V(IV) is oxidized to V(V) with air. During this phase it is also important to monitor the V(V) concentration, in order to speed up the return of the reoxidized vanadium to the absorption circuit. A method was required that would be capable of determining V(V) in an alkaline medium, in the presence of up to a 10-fold excess of V(IV). The monitoring and control was successfully applied in a process analyzer with an FIA manifold illustrated in Fig 6.^{44, 57}

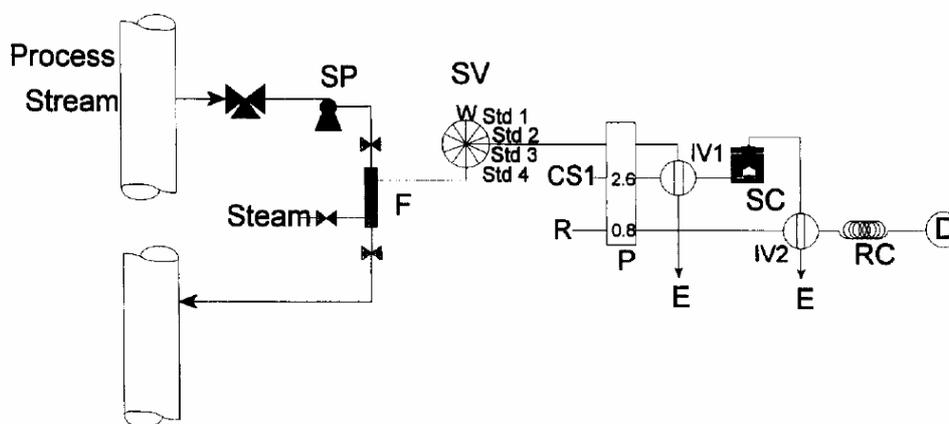


Fig. 6 – FIA manifold and sampling system used in the process analyser. SP=centrifugal pump; F=0.2µm ceramic cross-flow filter; SV=selection valve; P=peristaltic pump; W=wash solution; Std 1-4=calibrant solutions; CS1=5 mmol/l CDTA stream; R=6.8x10⁻⁵ mol/L PAR, 5 mmol/l CDTA, 0.1 mol/l phosphate buffer pH 5.3; E=effluent; IV1, IV2= injection valves; SC=stirred chamber; RC=2.5 m reaction coil; D=LED photometer at 550 nm. Reproduced from Ref. 57.

CPAC AND NeSSI

Process Analytical Chemistry (PAC) and PAT is not new and has been applied in the petroleum and petrochemical industries since the 1950s, but the demands for real-time quantitative chemical information near chemical plants on a growing list of manufacturing processes presented new challenges to analytical chemists, instrument engineers and plant supervisors. In response to these needs, the Center for Process Analytical Chemistry (CPAC) was established in 1984 at the University of Washington in Seattle as the Brain-child of Bruce Kowalsky to work with industry.⁵⁸ NeSSI (New Sampling/Sensor Initiative) was born from CPAC in focus group meetings held in 1999 followed with early work that was started in July, 2000 by Peter van Vuuren (ExxonMobil Chemical) and Rob Dubois (Dow Chemical) with the initial aim of adopting new types of modular and miniature hardware which were being addressed as a standard for industry being developed by an ISA (Instrumentation, Systems and Automation Society) technical committee. Both Peter van Vuuren (ExxonMobil Chemical) and Rob Dubois (Dow Chemical) introduced and promoted the vision and future concepts of a communication/power bus specifically designed for process analytical control (the NeSSI-bus) and fully automated sampling systems at a presentation at the International Forum of Process Analytical Chemistry (IFPAC) at Amelia Island, Florida, USA in January 2001 with the idea to implement modular, miniature and automated (smart) sample system technology using the mechanical design based on

the American National Standards Institute/Instrumentation, Systems and Automation Society (ANSI/ISA SP76.00.02-2002) standard.⁵⁹ The vision and mission of the Nessi concepts include 3 generations with Nessi I in the time-frame 2000-2002 implementing mechanical, passive components on a SP76 BUS (train) substrate, Nessi II in the time-frame 2000-2002 with “electrified” passive & active components on a SP76 bus substrate, integral heating and temperature control of the substrate, all electrical components integrated with a sensor/actuator manager (SAM), sensors and actuators communication via a sensor bus and smart (self-diagnostic) sample systems and Nessi generation III from 2003 onwards having many analytical sensors and micro-analytical systems and also wireless sensors. In the presentation of Peter van Vuuren at IFPAC2008, NeSSI Day, Baltimore, MD, USA, 29 January 2008 with a title of the New Sampling/Sensor Initiative (NESSI)- An enabling platform for the reduction in Total Cost of Ownership (TCO) of process analytical systems, he presented a NeSSI BUS Platform with the sampling system and flow channel substrate with all the components included to move samples to a micro GC analyzer and the spectroscopic microanalyzers.⁵⁹ The NeSSI BUS Platform system was and is still very successful with the implementation in numerous petroleum and petrochemical industries. The current technology of NeSSI uses on-site (at-site) on-line analysis where the sample is automatically sampled and fed into a dedicated analysing system where analysis is automatically performed with an automatic feedback to the operating system (for example, process stream for industrial chemical processes) for adjustment and corrective action with their analytical system (sensors, detectors) close to the sampling point (by-line) with close-time monitoring or near real-time monitoring.²⁶

FROM PAT TO TAP

The increasing demand from the petroleum and petrochemical and other relevant industries in the 1990s to real-time integrated process monitoring and control was followed by numerous attempts, developments and implementation of process analyzers leading eventually to the PAT concept from the continuous flow viewpoint and various aspects of automated non-destructive spectroscopy with the first version of non-destructive scanning spectroscopy introduced by the Chemistry Department in Pretoria that lead to the first PAT type configurations with chemometrics and the second road crossing road one. These were the first attempts to integrated real-time process monitoring and control with the future vision of in-line analysis, where the analysing probe is situated inside the operating system (or plant) as part of the operating system (or process stream). Transduction is performed inside the operating system with a feedback to the processor inside if possible or outside the operating system with facilities for fast automatic adjustment and fast immediate corrective action.²⁶

THE TAP ERA

There was also an increasing need from industries to follow the kinetics of very fast reactions in heterogeneous catalytic reactors and membrane reactors and this led to the idea concept of temporal analysis of products (TAP). The TAP reactor system was originally initiated by John Gleaves in the late 1980's⁶⁰ as an interrogative kinetics approach to assist the catalytic development approach and is proving to be a powerful tool for unraveling complex catalytic reactions and other surfaces processes and a powerful technique to investigate the mechanism and kinetics in heterogeneous catalysis. With fast, transient measurements and a high time resolution it is possible to determine single reaction steps during a reaction over real catalysts. Interrogative kinetics (IK) is based on the application of novel high speed transient response experiments (TAP pulse response experiments)^{60,61} in conjunction with traditional kinetic measurements (steady-state, TPD, step-transient. etc.). IK uses a battery of kinetic measurements to probe the kinetic characteristics of a catalytic surface, and to monitor how these characteristics change in response to changing reaction conditions (pressure, temperature, surface coverage, reactant composition, etc.). A simplified schematic diagram of a TAP Knudsen pulse response experiment is outlined in Fig. 7.⁶² A narrow gas pulse is injected into an evacuated reactor containing a packed bed of catalyst particles. The gas flow exiting the reactor is detected by a quadrupole mass spectrometer (QMS), and is determined as a function of time. The resulting transient responses of reactor output reflect the transport and kinetic processes that occur

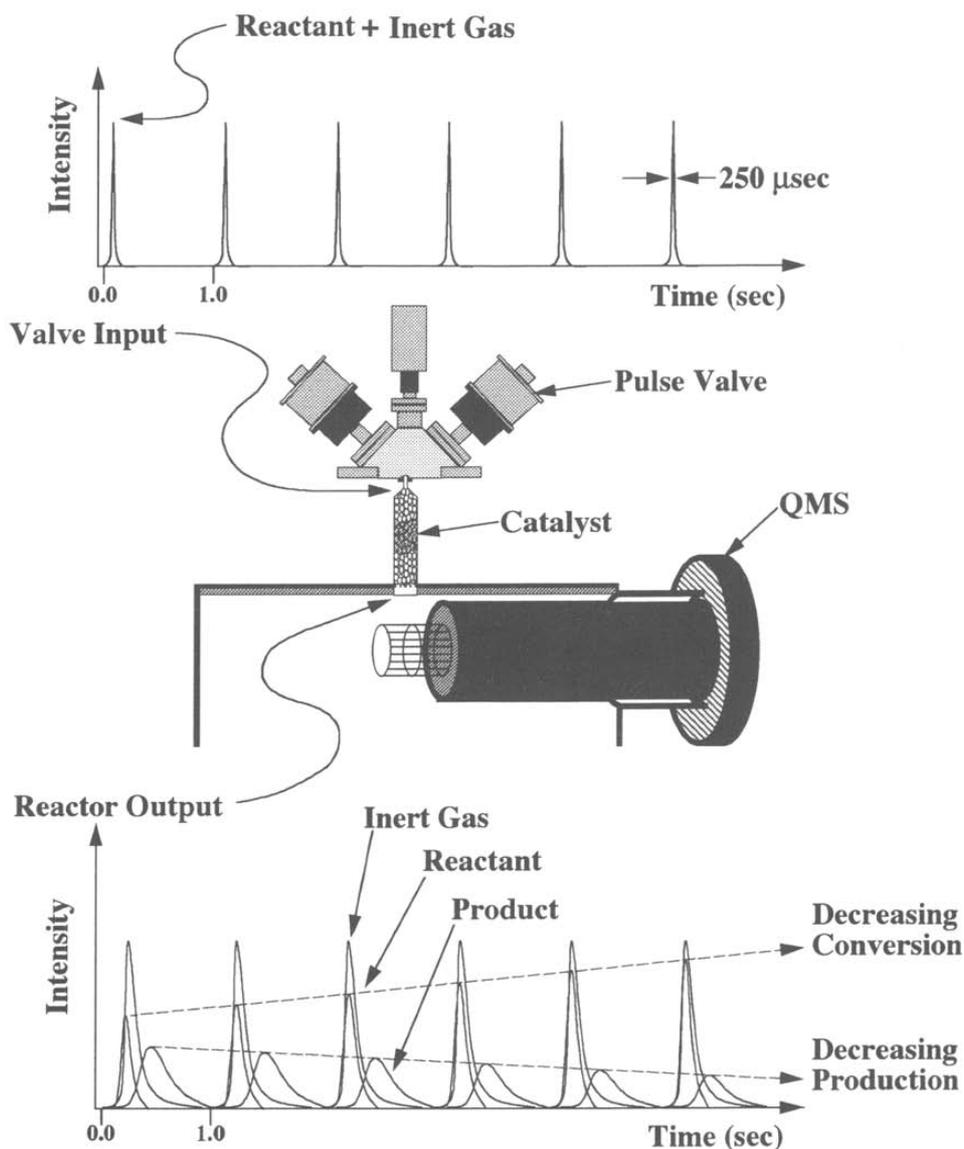


Fig. 7 – Simplified schematic diagram of a TAP Knudsen pulse response experiment. Reproduced from Ref. 62.

in the reactor.⁶³⁻⁶⁵ In a publication on the recent advances in technology for kinetic analysis of multi-component catalysts the TAP-3 reactor system (Fig. 8)⁶⁶ is comprised of (1) a pulse-valve manifold assembly that supplies gas reactants for pulsed and flow experiments at user defined temperatures and pressures, (2) a microreactor assembly that can be operated isothermally or in a temperature programmed mode, (3) a mass spectrometer detector contained in a high-throughput ultra-high vacuum system, and (4) a computer based control and data acquisition system. The TAP-3 menu of experiments includes, high-speed vacuum pulse-response experiments (TAP Knudsen pulse-response experiments, TAP pump-probe experiments, and TAP multi-pulse experiments, pulse experiments with a change of time within a pulse and between pulses), atmospheric pressure steady-state, step-transient and Steady-State Isotopic Transient Kinetic Analysis (SSITKA) experiments, temperature programmed desorption (TPD), and temperature programmed reaction (TPR). In addition, newly developed software allows the user to create programmed experimental sequences, which can be stored in memory, and then performed automatically. Sequences may include complex temperature treatments, switching back and forth between atmospheric pressure and vacuum experiments, switching from continuous flow to transient response experiments, or combinations of step-transient, pulse transient, steady-flow, and temperature programmed experiments. The development and implementation of

various commercial versions of the TAP reactor system indicate the success of the concept to both academic and industrial research groups. It opens however a new innovation paradigm of new non-destructive probe systems and TAP where a variation and adaption of the TAP concept and approach in the future can be redesigned, developed, applied and implemented in industrial shaped potential areas for non-destructive invasive and/or non-invasive process analytical technologies with probes of micro-detection systems like NIR, MIR, UV-Visible, Raman Scattering (SERS), MS, NMR, Tetrahertz microwave, Acoustic techniques, Sensors, Fluorescence, Chemiluminescence with chemometrics for process optimization and process intensification either in flow or with discrete systems.

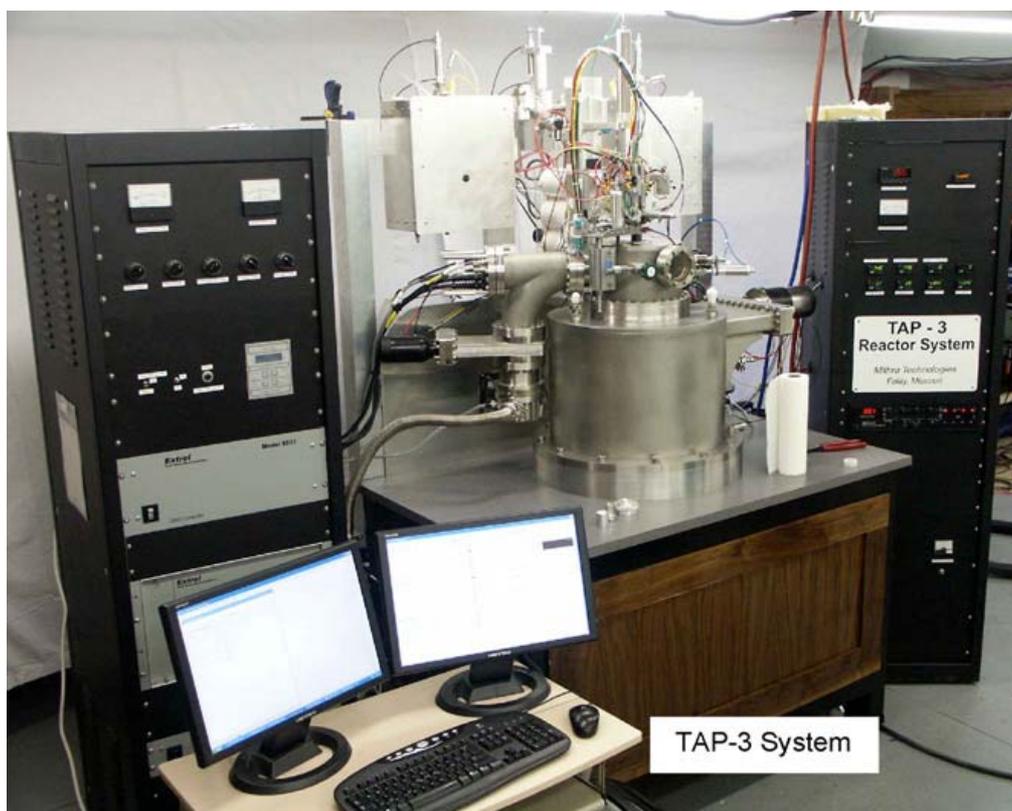


Fig. 8 – The TAP-3 Reactor System. Reproduced from Ref. 66.

CONCLUSIONS

Looking at the various innovation aspects of instruments design, development, implementation and application from chromatography to flow systems, FIA, SIA, PAC and PAT and eventually to the temporal analysis of products (TAP) concept with the latest TAP concept, does these innovations and exploitations satisfied the need of the modern industrial world? A future vision of invasive and non-invasive non-destructive real-time integrated multi-analyte fully automated interactive process analyzers as incentives and new paradigm concepts of innovative, low cost, easy to operate, portable sensing platforms with an interrogative kinetics approach for fast, transient measurements and a high time resolution in industrial processes up to Real-time Integrated Industrial Monitoring and Control Information Management Systems should satisfy most of the requirements of industry. However the fully in vitro in situ in-line complete fast intelligent interactive non-destructive process analyzers to manage complete process reactions at various positions inside process plant pipe-lines with fully automated non-attending supervision for extended periods to deliver high quality industrial products still do not exist.

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Abbreviations

ANSI	American National Standards Institute
CFA	Continuous Flow Analysis (Analyzer)
GC	Gas-Chromatography
GLC	Gas-Liquid Chromatography
GIPM	Good Industrial Process Management
CPAC	Center for Process Analytical Chemistry
FIA	Flow-injection analysis
GTL	Gas-to-liquids
IFPAC	International Forum of Process
IK	Interrogative Kinetics
ISA	Instrumentation, Systems and Automation Society
LIMS	Laboratory Information Management Systems
MID	Mid-Infrared
MIMS	Manual Information Management Systems
NATREF	National Petroleum Refiners of South Africa
NeSSI	New Sampling/Sensor Initiative
NIR	Near Infrared
NMR	Nuclear Magnetic Resonance
NSFS	Non-Segmented Flow Analysis
SAM	Sensor/Actuator Manager
PAC	Process Analytical Chemistry
PAT	Process Analytical Technology
PPMT	Process Product Measurement Techniques
QMS	Quadrupole Mass Spectrometer
RIIMCIMS	Real-time Integrated Industrial Monitoring and Control Information Management Systems
SASOL	Suid-Afrikaanse Steenkool-, Olie- en Gaskorporasie (South African Coal-, Oil- and Gas-corporation)
SERS	Surface Enhanced Raman Scattering
SFA	Segmented Flow Analysis (Analyzer)
SIA	Sequential Injection Analysis
SMA	Sequential Multiple Analyzer
SMAC	Sequential Multiple Analyzer with Computer
SPCAS	Smart Process Control Analyzer Systems
SSITKA	Steady-State Isotopic Transient Kinetic Analysis
TAP	Temporal Analysis of Products
TPD	Temperature Programmed Desorption
TPR	Temperature Programmed Reaction
TQISM	Total Quality Industrial Sustainable Management
UV-visible	Ultraviolet Visible

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