Deep Trek
Re-configurable Processor for Data Acquisition (RPDA)

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Technology Status Assessment

To

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Author:
Bruce Ohme
Honeywell International Inc.
Honeywell Aerospace D&S
12001 Highway #55
Plymouth, MN 55441- 4799

DOE Project Officer:
Jamie Brown
National Energy Technology Laboratory, MS E06
3610 Collins Ferry Road
Morgantown, WV 26507-0880

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1.0 Introduction

This report comprises a Technology Status Assessment pertaining to Honeywell's Re-configurable Processor for Data Acquisition (RPDA) project. The objective of this project is to develop a high-temperature (HT) (>225°C/437°C) re-configurable digital processor module to manage data acquisition for deep oil and gas drilling and production monitoring systems. This project addresses the need for flexible data management and interface functions within high-temperature/high-pressure data acquisition systems.

2.0 Current State of Technology

The Need to Develop Electronics for Deep-drilling

Electronics are widely used in modern oil and gas exploration, drilling, and production. The ability to measure conditions down-hole has changed the economics of drilling and production such that producers will not consider drilling without the means to send electronic instruments down-hole. Because drilling rigs are very expensive to operate, the ability to collect data while drilling has become indispensable. Data that is collected by these services includes measurement of depth and heading, formation resistivity, back-ground gamma radiation, pressure, temperature, strain on the drill string and/or bit, vibration, seismic response, rotation, and others factors. These data help the operator monitor drilling progress and direction, assess the condition of drilling hardware and processes, and learn about the strata and fluids that are encountered. Taken together, these data collection capabilities change the entire risk profile of drilling projects and make previously inaccessible assets economically viable.

The ability to collect data down-hole is even more important when the target reservoir is very deep. As bore-hole depth increases, mechanical and environmental problems become more severe. Rates of penetration go down as rock becomes harder, reservoir pressures and temperatures increase, and the mass of the drill-string and volume of drilling fluid increase making the drilling process harder to control. Furthermore, as it takes longer to traverse from surface to the bottom, the consequences of damaged hardware or instrumentation, of backing up to drill around broken hardware, or of missing the target, go up drastically. It is a high-stakes gamble, and no wonder that producers insist on highly reliable means to monitor the drilling processes before they are willing to even begin.

The single biggest obstacle for electronic data acquisition systems in very deep wells is the HT encountered at great depth. Commercial electronics are not designed for these temperatures, and conventional integrated circuit (IC) technology is not capable of operating at these temperatures. The approaches for down-hole electronics for oil and gas exploration and production are presently determined by the nature of the service that is being deployed and the environmental requirements. Down-hole electronics services include wire-line logging, measurement-while-drilling (MWD), and post-completion production monitoring applications. Each of these represents successively greater challenges in terms of the time-temperature profile that must be endured in order to provide the service.

Electronics for HT Well Instrumentation

Different approaches to electronics are employed depending on well-temperature. Modern electronics are predominately silicon ICs, supported by small numbers of discrete passive devices such as capacitors, inductors, and resistors. Commercially available consumer electronics IC's and packaging approaches are limited to a maximum operating temperature of about 75°C/167°F. Above this temperature plastic packaging is not reliable and the design functionality is not guaranteed. For military, industrial and some automotive applications ICs are commercially available for operation at 125°C/257°F or 150°C/302°F, respectively. These typically use ceramic packages which are more costly but able to withstand high-temperatures. Above 150°C/302°F the number of commercially available electronics components is very limited. These are often limited to simple power-transistors and supporting passive components which can be operated at higher temperatures (up to 200°C/392°F) by de-rating the power level in the devices relative to normal operating specifications. Besides the individual components, HT electronic systems are difficult to develop because of higher-level assembly techniques (i.e., board-level materials and interconnections).

Historically, most down-hole oil and gas wells require operation to 150°C/302°F. These applications are often addressed by tool-designers who procure commercial-off-the-shelf (COTS) devices specified for operation at lower temperatures (such as 125°C/257/°F). These are then screened (i.e., re-tested) by the tool-makers for operation at higher temperatures and used above their specified operating temperature range. Because operation at higher temperature usually involves degraded reliability, these components and/or boards are often used for a limited time (perhaps a few hundred hours) and then replaced. Another technique employed in wire-line applications is to thermally insulate the electronics (i.e., put them in a "Thermos bottle"), but this technique has limited time-of-use and temperatures limits.

Down-hole operators and producers are demanding electronics that operate in wells that see temperatures ranging from 170°C/338°F all the way up to 250°C/482°F. The "screen and throwaway" approach is not practical at these temperatures. The fundamental HT limitation for IC functionality at these elevated temperatures has to do with the way the electronics are designed and manufactured. The fabrication processes generally rely on semiconductor device isolation techniques (P-N junction isolation) that leak current badly at high-temperatures. In addition, fabrication processes developed for conventional temperatures result in transistors that are optimized for those temperatures….they may be seriously compromised in performance at extreme temperatures.

Alternatives to Conventional Silicon ICs

Alternative IC processes may be employed for HT applications. Beyond silicon, other semiconductor materials have characteristics that make them candidates for HT operation (some even higher than 300°C/572°F). Such materials include silicon carbide (SiC), Gallium Arsenic (GaAs), Gallium Nitride (GaN), and diamond. GaN and diamond are still in the research phase. Silicon carbide is the most mature of these technologies and can be used especially for discrete power devices, but has disadvantages in terms of lacking a viable MOSFET (Metal-Oxide-Silicon Field-Effect Transistor) structure, a high defect density, and process integration issues that make it difficult to apply for complex ICs. Gallium Arsenide has never really established itself as a competitor to silicon except in niche high-speed markets and suffers from mobility mismatch between n-type and p-type material. Another new device type is Silicon germanium (SiGe) bipolar transistors which are integrated with conventional CMOS (Complementary-MOS) devices for very high-speed applications. SiGe may have some wide-temperature range advantages, but requires integration with non-conventional CMOS, such as Silicon-0n-Insulator (SOI) CMOS for a complete HT capability.

Overall, SOI CMOS is the most viable, mature, near-term approach for addressing the HT data-acquisition system requirements. This silicon-based approach employs conventional silicon processing technology, but incorporates a transistor isolation process that does not leak current at HT. Instead of the traditional P-N junction isolation, SOI processes surround each transistor in silicon-dioxide (i.e., "glass") which has excellent electrical isolation properties that do not degrade at HT.

Current Status of SOI Electronics for HT

An SOI process, HTSIO4, has been developed and commercialized by Honeywell under the Deep Trek HT Electronics project that was awarded in 2003 and is due to complete in 2007. Under that project Honeywell has demonstrated the HT capability of SOI, including operation of components as high as 375°C/707°F. Honeywell's efforts take advantage of the SOI technology, but also include design, assembly, and testing infrastructure and techniques that specifically address HT applications. Honeywell's first 225°C/437°F SOI components were marketed in 1995. SOI has also recently been employed by a European supplier (CISSOID) to offer additional HT IC components, including a voltage reference, positive/negative voltage regulators and an oscillator/timer chip. Some government and industry efforts have also been directed to SOS (silicon-on-sapphire) ICs fabricated in Australia by Peregrine Semiconductor. These include digital logic libraries and circuits as well as some analog signal processing functions. SOS is manufactured using process that starts with an aluminum-oxide insulating starting material upon which crystalline silicon is deposited, whereas SOI starts with crystalline silicon and introduces silicon-dioxide as an insulator through various processes. Both SOI and SOS technology are used by the electronics industry, although SOI is much more prevalent At this time CISSOID and Honeywell are the only commercial sources of SOI components for HT (>200°C) operation. At this time there are no commercially available SOS components for HT.

HT IC Component Gaps and Commercial Obstacles

As appropriate SOI technologies are proven to be capable, the next hurdle to be overcome is to provide a sufficient range of functions and features. While there are diverse applications for down-hole electronics, these are low-volume by the electronics' industry standards. The non-recurring costs to develop new electronic functions are relatively high. Further complicating the issue are the extreme space limitations and harsh mechanical environments down-hole, including vibration, thermal cycling, and thermal fatigue. These problems require solutions that utilize HT SOI processes, minimize development cost for low-volume applications, and provide the electronics in packages that conform to the physical size constraints, temperature extremes, and harsh mechanical environments down-hole.

Addressing Low-volume Commercialization Issues With Programmable Devices

Low-volume digital applications at conventional temperature ranges are often addressed by the use of programmable logic devices. These go by a variety of names, including FPGAs or Programmable Logic Devices (PLD). The low-cost and ever increasing levels of functionality for which the IC industry has become famous are the result of economy-of-scale achieved by batch processing and high-volume manufacturing. FPGA's and PLD's apply these economic advantages to low-volume or application-specific digital components by enabling the user to customize, on a unit-by-unit basis, components that are manufactured in high volumes. An FPGA, for example, can contain hundreds of thousands of logic gates where the connectivity (and thereby the functionality) of the unit is "programmed" for each individual component.

Addressing Configuration Issues of Programmable Devices

Programming means for FPGA's or PLD's may allow for one-time programming or for re-programmability. One-time programmable (OTP) devices are programmed electrically by directly applying "programming voltages" across elements in the circuit to create opens or shorts between conductors that are not there prior to programming. OTP FPGA's are not available in HT processes (such as SOI) and the long-term reliability of the programming means at high-temperatures has not been established.

Re-programmable devices provide flexibility. Unlike OTP devices, these can be programmed multiple times, in potentially different ways. Re-programmable FPGA's rely on some type of non-volatile memory (i.e., a memory that, once programmed, retains its data if power is interrupted). The data in the non-volatile memory programs the connectivity (and therefore the functionality) of the FPGA. Re-configurable FPGA's may have the non-volatile configuration data stored in non-volatile memory embedded within the FPGA chip, or they may rely on external means for storing the data and require configuration each time the FPGA is powered up. Regardless of the approach, re-configurable FPGA's have not been available for HT applications because they have not been built within a HT process (such as SOI). Beyond that, HT non-volatile memory has not been available. However, both the FPGA and non-volatile memory gap will be filled by Honeywell's existing HT electronics project.

HT Multi-Chip Packaging

High-reliability HT packaging is an essential element of the down-hole electronics system. Co-fired ceramic Multi-Chip Modules (MCM's) meet this need with stable performance at temperatures greater than 225°C/437°F. In down-hole systems reliability is improved by reducing the number of device inter-connections that need to be made at the circuit board level. An MCM can be likened to an electronics board implemented in a single solid piece of ceramic material. In this process, layers of ceramic materials (such as Alumina, Al_2O_3) are alternated with patterned layers of interconnect metalization (such as Tungsten) that are built into a multi-layered structure and then fired to result in a single, hermetic ceramic package. Multiple die can be attached in such a package using gold-eutectic die bonds or HT adhesives and wire-bonded to internal package interconnect traces. External pins can be brazed onto the ceramic body where external metalization is plated with gold for long-term HT applications. Lids made of Kovar (Ni-Fe-Co) that are well matched to the thermal expansion properties of the ceramic can be soldered using HT Au-Sn solder or else welded to Kovar seal rings built into the ceramic. This technology results in high density, hermetically sealed packaging with short internal wire lengths that is extremely tolerant of shock and vibration and capable of withstanding extreme temperature cycles.

3.0 Development Strategies

<u>Technology/Methodology Proposed</u>

The technology and approach chosen addresses the simultaneous need for HT operation, low component development cost, and small, rugged packages. Under the current Deep Trek HT Electronics project, Honeywell has developed, via their HTSOI4 process, a 30,000 gate FPGA and is developing a 32K x 8 EEPROM which are both developed for operation at 250°C. This project will combine these elements with a third component, a 32K x 8 SOI static RAM (SRAM), in single package tailored to the physical constraints of down-hole MWD and production monitoring applications. The resulting RPDA module is a re-configurable processor in a rugged down-hole package with I/O capability to: (1) Collect data from multiple Analog Front Ends; (2) Handle parallel/serial inputs; (3) Control analog-front ends (gain, input, sleep, etc), (4) Communicate on a variety of system busses; (5) Autonomously configure itself on power-up; (6) Store calibration coefficients, module ID, and/or data in non-volatile memory.

<u>MCM Hardware and FPGA Configuration Development Criteria</u>

The objective of the RPDA is to enable realization of a wide range of Data Acquisition systems from a limited suite of hardware components, at low development cost. As shown in Figure 1, the RPDA could support Analog-Front Ends (AFE's) within a data acquisition covering a broad range of update rates and resolution, using either serial or parallel data transfer formats. The RPDA could provide control signals for these AFE's that could be used for input channel selection, programmable gain controls, power-management controls (such as shut-down or idle modes), or other configuration functions. On the other side, the RPDA could share digital outputs on a simple parallel or serial interface bus.

As previously mentioned, the idea is that the RPDA can support the functionality of a data acquisition digital interface processor using SOI CMOS components that are already developed or being developed. These components would be offered in a new MCM package configuration with the FPGA configured to provide the data acquisition functionality. Major elements of this project therefore are package development and FPGA software configuration development. Since the RPDA is re-configurable, the same hardware could serve in a wider range of applications than is proposed here simply by developing new FPGA configurations for the RPDA (as opposed to requiring hardware development).

The overall result is akin to having a flexible micro-controller with built-in non-volatile instruction memory and data memory in a single package. The package would be developed to have rugged through-hole pins in a dense pin-grid array (PGA) pattern with an overall width profile of 0.7" or less, allowing ease of use in down-hole tools and instruments.

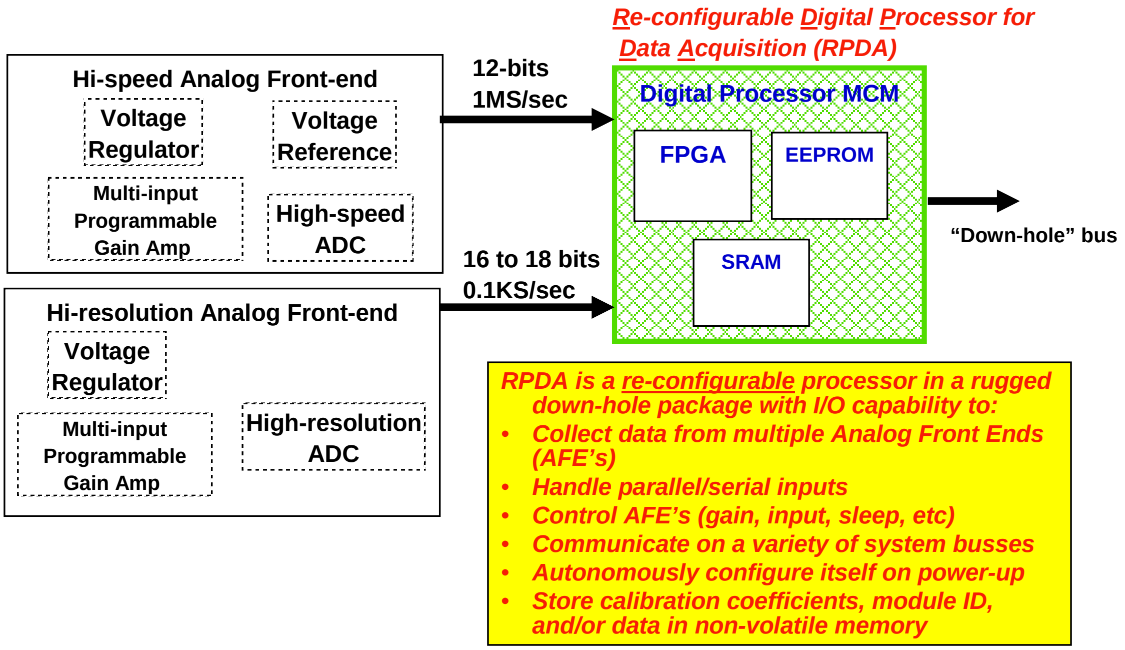

Figure 1: RPDA – Target Application & Features

HT FPGA Utilization

FPGA are a good alternative to dedicated hardware designs where low up-front costs and/or fast-turn development are requirements. FPGA's allow users to define functionality of individual hardware units after it has been delivered by the manufacturer or even after it is assembled into a board or deployed in an application. This FPGA is a fully licensed functional equivalent to a standard-temperature commercial product, the AT6010 FPGA manufactured by Atmel. Replicating an existing commercial product obviates any program requirements developing and supporting hardware or software development systems for FPGA configuration. The FPGA is re-configurable, has a capacity of up to 30,000 usable gates (up to 6,400 registers), and has up to 204 user-defined Input/Output (I/O) pads. Configuration is controlled by dedicated configuration pins and dual-function pins that double as user I/O pins when the device is in operation. The FPGA can be partially reconfigured while in operation; portions of the device not being modified remain operational during reconfiguration.

HT EEPROM Utilization

Since the FPGA has a volatile configuration, the configuration is not preserved through a cycling of the power supplies. Therefore an external means for storing the configuration data is required. Configuration data can be loaded into the FPGA upon power-up. In the case of the RPDA, configuration data storage and up-load is provided by the non-volatile EEPROM. EEPROM refers to memory that can be both written/read multiple times and that retains data when power is interrupted. It is “read-only” not in the sense that it literally can’t be re-written, but in the sense that write-access time is typically orders of magnitude longer than read-access time. However, within the EEPROM there is memory capacity beyond that needed to configure the FPGA. Other uses for this memory include storing instruction code, storing hardware configuration data such as serial numbers and calibration coefficients, and data logging.

The HT EEPROM to be used will have a capacity of 256Kbits organized as 32K x 8 bits, and is expected in 2007. The EEPROM incorporates the functional equivalent of an industry standard parallel-interface 28C256 EEPROM. Some additional hand-shake control features will be added to the EEPROM so that configuration of the FPGA can be completed automatically each time the devices are powered up.

HT SRAM Utilization

The final integrated circuit within the RPDA is a 32K x 8 SRAM which provides additional data memory and can be written at speeds much faster than an EEPROM. This component is an SOI CMOS component that is commercially available from Honeywell with specified operation at 225°C. Placing all three components into a single MCM package enhances performance and reliability. It is desirable for both throughput and functional simplicity to provide parallel connections between the “processor” (in this case the FPGA) and its supporting memory address and data busses. This however requires a large number of inter-connections and providing this connectivity on a board would consume a large area and compromise overall reliability. Partitioning the system to include the memory interfaces within the MCM embeds all of these interconnections within the co-fired ceramic and takes this burden away from the board layout.

Another advantage of developing the RPDA package is that it provides a general-purpose down-hole friendly housing for the FPGA with a companion EEPROM that can be used for non-volatile FPGA configuration data storage.

4.0 Future Impact

At the end of the program, tested samples of the configured RPDA module would be delivered to the Dept. of Energy along with a complete characterization and life-test report. Behavioral and/or gate-level hardware description language (HDL) models and FPGA configuration data files would also be provided, subject to any limitations on distribution that might apply from pre-existing or negotiated license agreements.

This project will deliver the RPDA module as a configured device for data acquisition system applications. However, since this is a re-configurable solution, the hardware developed within this project can be applied to other applications, including data processing, actuator controls, pulse-width modulator controls for DC-to-DC converters and other applications. The programmability will eliminate delays otherwise required by IC design and fabrication cycles. The RPDA provides a level of flexibility never before available in a single HT (up to 250°C/482°F) component. The RPDA will not require external non-volatile memory, can be re-configured, has I/O that can be programmed as input or outputs, and complete flexibility of internal functionality up to the limit of its capacity. The RPDA will be able to provide the “glue logic” and interfaces to enable inter-operability of many diverse components as they are developed by a diverse set of suppliers. As more functions are linked, producers will be finally able to deploy the systems they need to undertake deep drilling projects. This may lead to further industry development of new tools and instruments. There is the potential for a “snowball” effect that will help to open up the development of deep oil and gas resources.

<u>Commercialization</u>

This project is expected to make the RPDA ready for market introduction. Subsequent commercialization tasks, undertaken by Honeywell may further develop and/or refine the product offering. Initially, the product that will be offered will be a HT hardware deliverable incorporating an SRAM, FPGA, and a “blank” EEPROM, in a rugged multi-chip package suitable for HT, down-hole applications. In other words, Honeywell would provide an “un-configured”

FPGA. The hardware module will also incorporate high-temperature ceramic chip capacitors (some capacitors are required for power-supply noise filtering while others are required by the HTEEPROM; these will be selected from several vendors offering high-temperature capacitors. Other deliverables and services associated with this product may also be developed. This could include:

- Selling MCM-targeted functions in the form of FPGA configuration files and/or hardware-description-language (HDL) formats (such as Verilog).
- Selling fully configured and tested MCM's, with FPGA configuration data already embedded within the EEPROM.
- Promoting and/or supplementing sales with supporting documents such as application notes, synthesis and configuration instructions
- Providing development boards and/or hardware configuration loaders
- Providing HDL simulation models for the EEPROM and/or SRAM
- Providing configuration and test services.

<u>Beneficiaries</u>

Oil and gas industry down-hole tool suppliers and oil/gas service companies are the most likely direct buyers of the RPDA, but producers are likely to receive the greatest overall benefit. This technology may be used for HT/high-pressure well-logging, MWD, and DWD applications. Because the electronics are capable for long-term reliable operation at elevated temperatures, this technology supports down-hole permanent-installation for production management as well. Other markets with needs for HT electronics, such as distributed controls for turbine engines and avionics, are expected to benefit from this product offering as well.