WHITE PAPER

Small Modular Reactors Demand Advanced Data-Acquisition

Small modular reactors (SMRs) are advanced nuclear fission reactors. The “modular” portion of their name refers to the fact that they can be built in one location (such as a factory) and shipped, commissioned, and operated at a separate site.

SMRs have power generation capabilities ranging between 30MW and 300MW, depending on their type. With a footprint less than a tenth that of a traditional nuclear reactor, SMRs are of interest for industrial and scientific applications that require a lot of power. They also offer advantages concerning deployment in remote areas with limited (if any) grid capacity.

Although SMRs are a relatively new concept, the first systems have already been deployed, and—at the time of this writing—there are more than eighty different designs currently under development in 19 countries.[1]

What About Renewables?

The use of renewable energy sources with small carbon footprints like solar energy, hydroelectric (including tidal energy), and wind power is ramping up, accounting for approximately 23% of US electricity generation in 2023.[2] However, renewables are not always the answer—water may not be readily available for hydroelectric power generation, solar power is only obtainable during the day, and wind farms require a vast and obvious footprint.

In addition to being deployed in locations where renewables do not provide an option, SMRs also help battle the climate crisis and reduce greenhouse gas emissions.[3]

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The Main Components of an SMR

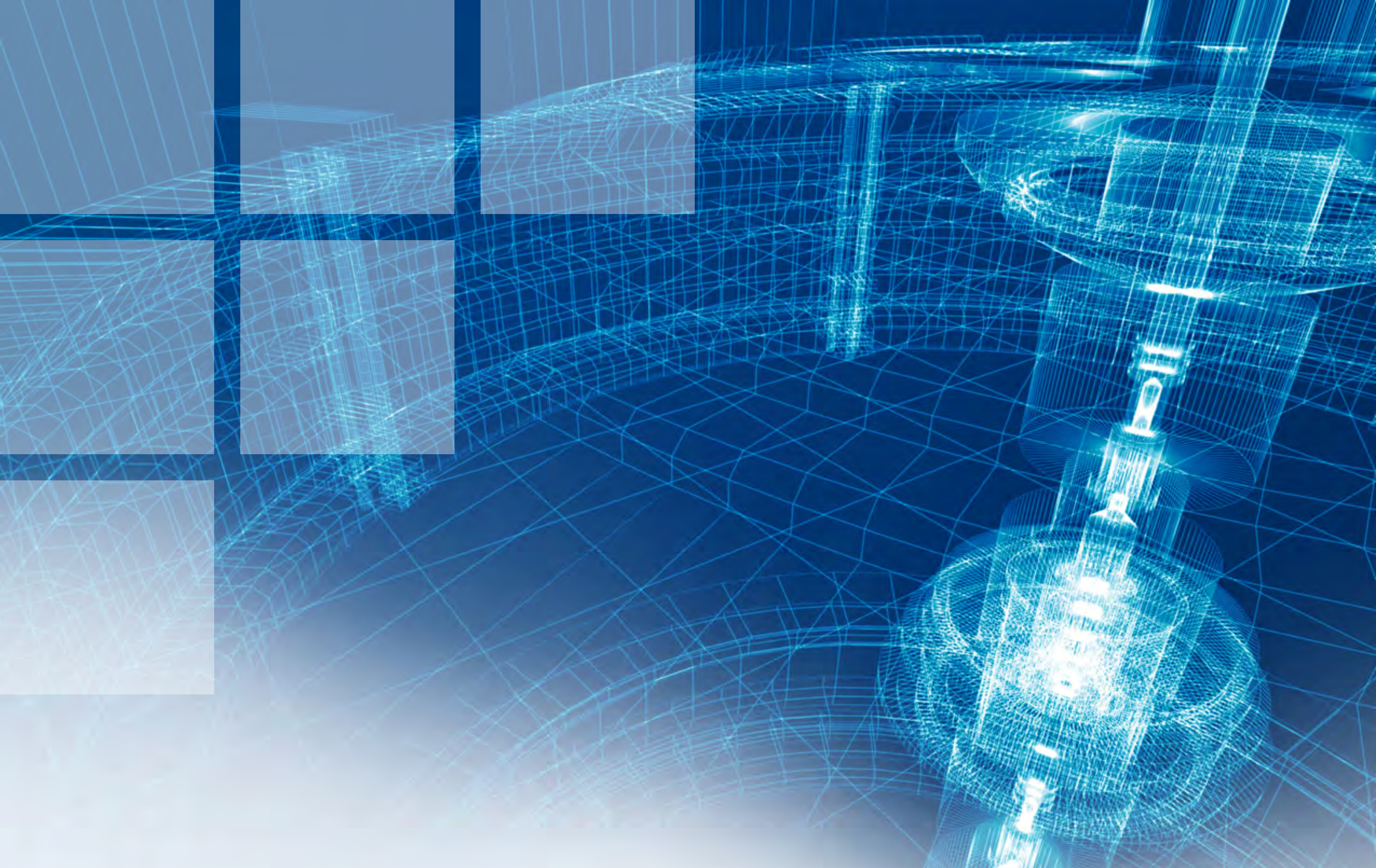
An SMR's heart is the reactor core containing the nuclear fuel consisting of fissionable material that generates neutrons, the control rods that absorb neutrons to control the reaction, and the containment vessel.

A new reactor is assembled with its control rods fully inserted. The control rods are then gradually removed from the core to allow the nuclear chain reaction to start up and increase to the desired power level. The positioning of the control rods is controlled using electric motors or hydraulic systems.

In most reactor designs, electromagnets attach the control rods to the lifting machinery, as opposed to direct mechanical linkage. This means that in the event of power failure—or in the case of an emergency shutdown initiated by a human or an automatic control system—the control rods fall automatically, under the influence of gravity, all the way into the pile to terminate the reaction. Quickly shutting down a reactor in this way is called scramming, and a typical shutdown time for modern reactors like SMRs is around two seconds.

Also, there will be a coolant circulation system that powers the turbine that drives the electricity generator. Some SMRs use water as a coolant, in which case pumps are used to push the water through the system. Heated by the reactor core, the water turns into superheated steam that powers the turbine. Other SMRs may use gas, liquid metal, or molten salt as coolants.

The primary consideration for this paper is that SMRs are composed of many parts, including pipes, motors, pumps, turbines, and generators, all of which need to be monitored and controlled.



Digital Twins

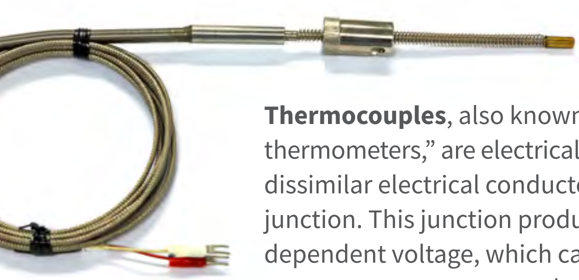
"Digital twin" refers to a digital representation as a high-fidelity model of a real-world physical product, system, or process. The digital twin can emulate the actual system for simulation, integration, testing, monitoring, and maintenance.

Although the concept originated earlier, the first practical definition of a digital twin was instigated in 2012 by NASA to improve the physical-model simulation of spacecraft. Since then, digital twins have proliferated throughout many industries, proving themselves invaluable for safety-critical and mission-critical applications like SMRs.

Digital twins are commonly divided into subtypes that include digital twin prototypes (DTPs), digital twin instances (DTIs), and digital twin aggregates (DTAs). A DTP exists before a physical product is used to evolve and verify the design before it is built. Once a real-world version of the product exists, each instance will have its own DTI. Inputs to the DTI can be based on information to the real-world system. Similarly, results from the DTI can be compared to results from the real-world system. Any discrepancies between the real and virtual worlds can be investigated to identify and resolve issues before they become problems leading to failures (potentially catastrophic failures in the case of SMRs). Finally, a DTA is the aggregation of DTIs whose data and information can be used for interrogation about the physical product, prognostics, and learning.

Sensor Types and Applications

A wide variety of sensors may be employed when developing and deploying an SMR. Three of the most common sensors are thermocouples, accelerometers, and strain gauges.

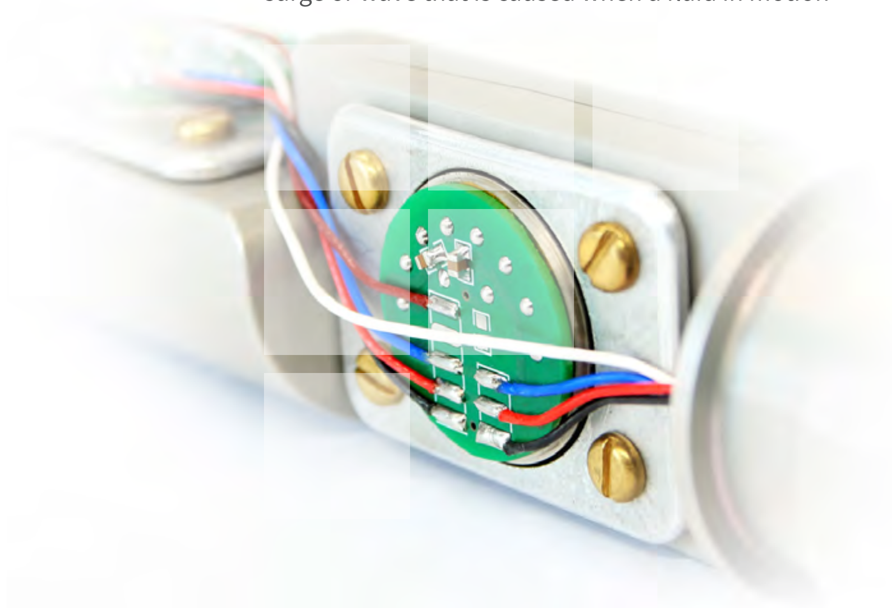


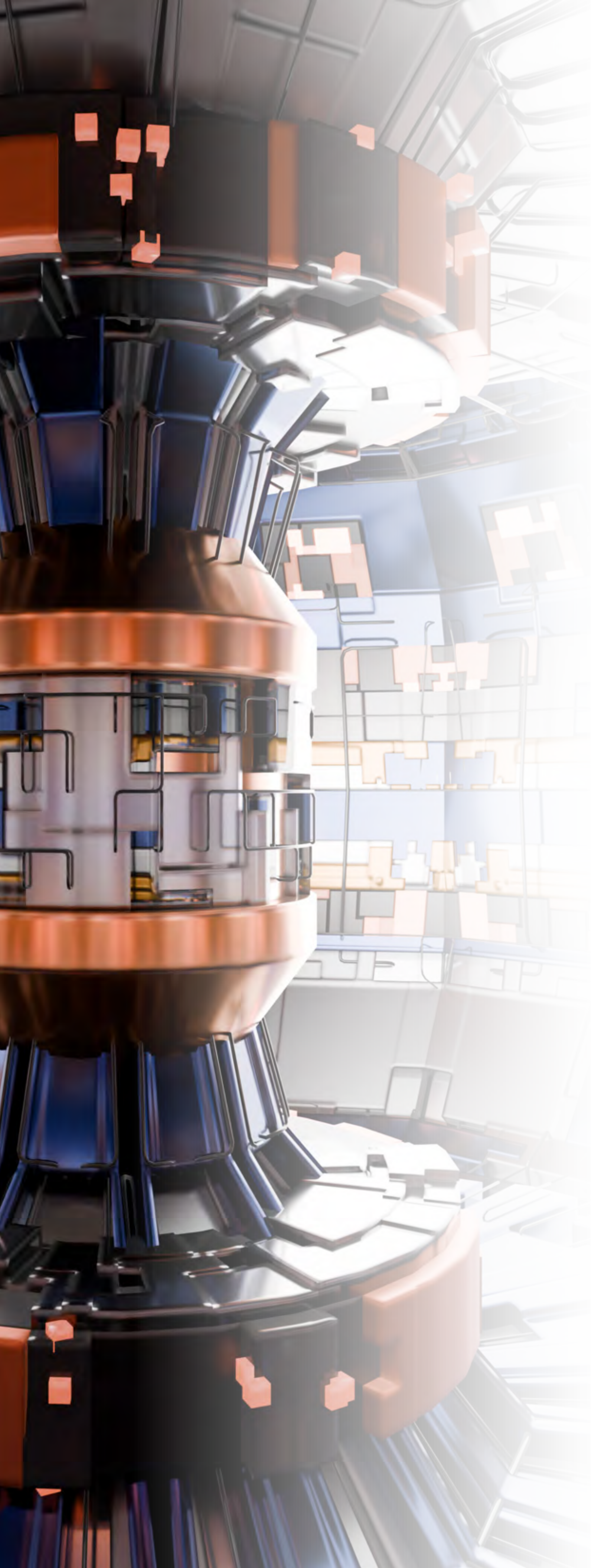
Thermocouples, also known as "thermoelectrical thermometers," are electrical devices consisting of two dissimilar electrical conductors forming an electrical junction. This junction produces a temperature-dependent voltage, which can be interpreted to measure temperature. In the case of SMRs, knowing the temperatures in various locations is essential because they can be used to detect out-of-bound conditions and thermal runaway. Furthermore, using a process known as "sensor fusion," the data from the thermocouples can be combined with data derived from other sensor types. The resulting information is less uncertain than possible when these sources were used individually.

Accelerometers may be used for a range of tasks, but one widespread application is to monitor vibrations in the system. In addition to motors and pumps, vibrations may be caused by the opening and shutting of valves and by acoustic perturbations associated with resonances in the system. Accelerometers can also be used to detect hydraulic shock (colloquially known as "water hammer"), which refers to a pressure surge or wave that is caused when a fluid in motion (usually a liquid but sometimes a gas) is forced to stop or change direction suddenly. This phenomenon commonly occurs when a valve opens or closes unexpectedly at the end of a pipeline, triggering a pressure wave that propagates through the pipe. These pressure waves can cause significant problems, from noise and vibration to pipe rupture or collapse.

The most common **strain gauge** type is insulating flexible backing supporting a metallic foil pattern. These are attached to different portions of the SMR's structure using a suitable adhesive. When the structure to which the strain gauge is attached is distorted due to the application of force, the foil is deformed, causing its electrical resistance to change. Strain gauges measure strain directly. These measurements can indirectly determine stress, deflection, torque, and deformation. In turn, the deformation of a pipe can be used to ascertain the pressure of the fluid (liquid or gas) in that pipe. In the case of SMRs, strain gauges are preferable to standard fluid pressure sensors that require holes and welds in the pipes, both of which proffer potential points of failure.

An additional consideration is that SMR reactors are more radioactive than larger reactors due to the smaller volume of the reactor core. As a result, they radiate significantly faster neutrons than larger cores, making everything in their surroundings more radioactive. This includes any steel pipes and walls. A simple pressure-sensing solution in the form of a strain gauge on a highly radioactive steel pipe is preferable to a broken pressure valve that requires replacement.





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R&D vs. Deployment

During the research and development (R&D) and prototyping stages on an SMR, hundreds, sometimes thousands of thermocouples, accelerometers, and strain gauges may be attached to every system portion. Readings from these sensors can be used to verify predictions based on computer-aided design (CAD) models, modify the design, and refine the digital twin prototype.

Another aspect of the R&D phase is determining the number and placement of any sensors to be used once the SMR is deployed to the field. Typically, only a few hundred sensors are employed in a deployed system instead of the thousands of sensors used in the prototype.

Readings from SMR sensors in the field can be used for a variety of purposes. In addition to feeding data to the digital twin instance and digital twin aggregate and detecting, identifying, and reporting problem conditions, this data can be used by artificial intelligence (AI) and machine learning (ML) algorithms to implement predictive maintenance algorithms. For example, by detecting and monitoring an anomaly in the vibrations associated with a pump, the AI can issue a prediction like, "This device will fail in 24 hours plus or minus one hour."

Who Are You?

IEEE 1451 is a set of intelligent transducer interface standards developed by the Institute of Electrical and Electronics Engineers (IEEE). These standards include a transducer electronic data sheet (TEDS)[4], a standardized method of storing transducer (sensors or actuators) identification, calibration, correction data, and manufacturer-related information. The material from the data sheet can be augmented with additional information, such as an identification name and/or number, along with the sensor's mission and physical location.

All this data can be stored in a small, low-cost (~$1) memory device, such as an EEPROM. This memory device may be mounted in the transducer itself, in the cable connecting the transducer to the measuring instrumentation, or in the connector at the point where it interfaces with the measurement instrument. The data contained within these devices is machine-readable and can be automatically accessed and employed by the instrumentation and higher-level monitoring and control systems.

TEDS can dramatically reduce the time required to establish and validate a system employing hundreds or thousands of sensors. Although the company may not be named for confidentiality reasons, a recent deployment in an aircraft prototyping environment involving 7,000 strain gauge channels without TEDS required two months to establish and validate. By comparison, a follow-up TEDS-enabled deployment on a different aircraft involving 10,000 strain gauge channels took only two weeks to establish and validate.

LAN eXtensions for Instrumentation (LXI) is a standard developed by the LXI Consortium, which maintains the LXI specification and promotes the LXI Standard. This standard defines the communication protocols for instrumentation and data acquisition systems using Ethernet. Although the LXI Standard embraces the TEDS concept, its support by an LXI-enabled instrument is not mandatory. As a result, not all instruments that are described as being LXI-compliant are capable of supporting TEDS.

What’s the Time?

Knowing the values being reported from many sensors is only useful if these values are associated with corresponding times. Establishing and measuring the temporal ordering of events requires those events to be timestamped. These timestamps must be related to a standard timescale synchronized to a typical “grandmaster clock” with sufficient accuracy and precision.

A variety of solutions may be employed, including connecting all the measuring instruments to a common external trigger. However, the preferred solution is the IEEE 1588 Precision Time Protocol (PTP) standard. By transferring timestamped packets back and forth between themselves, all the measuring instruments on the network can synchronize themselves to the grandmaster clock with sub-microsecond accuracy.

Having precise and accurate times associated with the data readings from the sensors significantly enhances the quality of information that can be extracted from this data.

Once again, although the LXI Standard embraces PTP/IEEE 1588, its inclusion in an LXI-enabled instrument is not mandatory. As a result, not all instruments that are described as being LXI-compliant are capable of supporting PTP/IEEE 1588.

Advanced SMR Data Acquisition

AMETEK Programmable Power's VTI Instruments brand provides a wide range of products and systems to monitor and record the data that characterizes the physical integrity and performance of large structures like SMRs.

Concerning the monitoring and control of SMRs—both during R&D and post-deployment to the field—VTI Instruments offers a suite of full-featured data acquisition families for use with strain gauges, accelerometers, and thermocouples.

For example, the EX1403A 16-channel precision bridge and strain instrument sets a new standard for strain and bridge measurements, delivering the highest performance measurements possible while controlling overall test hardware costs. With its ability to provide both constant voltage and constant current excitation, the EX1403A can measure all standard strain gauge configurations (1/4, 1/2, Full) and any standard bridge measurement (pressure, force, displacement).

The EMX-4350 smart, dynamic signal analyzer incorporates best-in-class analog design methodology to deliver industry-leading measurement accuracy. In conjunction with suitable sensors like accelerometers, this instrument is ideal for a wide range of applications, including noise, vibration, and harshness (NVH), machine condition monitoring, rotational analysis, acoustic test, and modal test, as well as general-purpose high-speed digitization and signal analysis.

Meanwhile, the EX1401 16-channel isolated thermocouple and voltage measurement instrument delivers accurate and highly repeatable thermocouple (±0.2°C) and voltage measurements by implementing fully integrated signal conditioning, providing 24-bit analog-to-digital converters (ADCs), and offering independent Cold Junction Compensation (CJC) on a per-channel basis.

In addition to supporting Power over Ethernet (PoE), these instruments are fully LXI-compliant, including support for PTP (IEEE 1588) and TEDS (IEEE 1451)‡ and all are enabled by associated data acquisition software, such as general-purpose, modal, and high-speed data acquisition packages.

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Conclusion

Over several decades, VTI Instruments has built an enviable reputation in test and instrumentation circles. For example, many instrumentation companies obsolete their solutions every few years, replacing them with newer, more expensive models. By comparison, although VTI Instruments are constantly reengineering our test and instrumentation solutions to take full advantage of the latest tools and technologies—possibly adding additional functionality—the new solutions remain identical in form, fit, and function to earlier devices.

This means that if you purchased a 100-channel solution a couple of years ago, and you need another 100 channels now, you don't need to throw everything away and start again—you can simply add another 100 channels. Although the new instruments may be more modern "under the hood," they will look and function the same and they will work seamlessly with your existing devices.

More recently, we have made our presence felt in the SMR arena. As a result, many companies and government-funded institutions are turning to VTI Instruments for their SMR-related test instrumentation and data acquisition solutions.

References

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± TEDS is not currently implemented in the EX1401 because a thermocouple sensor is not compatible with a TEDS EEPROM when using industry standard 2 pin mini TC connector.

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