Who's in Charge - Solutions for HEV/EV Battery Cell Management
Renesas Technology & Solution Portfolio

Microcontrollers
No.1 Market Share Worldwide

Advanced and Proven Technologies

System LSIs

Analog & Power
Extensive, High-quality Portfolio
Analog and Power Automotive Products

**40V-200V in Application Optimized Processes**
- Low voltage family optimized for $Q_{gd} \times R_{ds(on)}$
- Separate family optimized for pure $R_{ds(on)}$ performance
- Low RTH packaging technology

**6-200 mΩ Protected High-side Drivers**
- Scalable solutions for exterior lighting, relays, solenoids...
- Ultra-low key-off leakage current performance
- Robust protection against short-circuit conditions

**650V Discrete Devices**
- Class-leading turn-off loss
- High-speed, short-circuit rated, and low $V_{ce(on)}$ optimized
- 200A, 300A & 400A bare die

**Products Addressing All Major Vehicle Systems**
- Crash-sensing chipset for airbag applications
- Powertrain output load drivers, direct gas injection...
- Battery management ICs, MOSFET gate drivers
- Micro-isolator IGBT drivers for high-voltage isolation
- Multi-chip Package devices for switch input and load control
‘Enabling The Smart Society’

- **Challenge:**
  “The electrification of the automobile brings substantial challenges in it’s goal to contribute to the establishment of the Smart Society as a robust, efficient yet economical alternative to fossil-fuel-derived energy. Among the greatest challenges lies within the management of the single most expensive component of the electrified vehicle, the battery.”

- **Solution:**
  “Renesas battery management solutions couple high-accuracy performance with exhaustive protection and flexible architectures for optimal battery management systems.”
Agenda

Introduction to Battery Cell Management
- The Big Deal about Lithium Ion Battery Packs
- State of Charge (SOC) vs. State of Health (SOH)
- Methods for Determining State of Charge (SOC)
- Balancing Individual Cells to Optimize SOC
- A Typical Cell Balancing Algorithm*
- Example of Battery Management System
- Battery Management System Architectures

Battery Cell Management: Features of Merit
- ADC Cell Voltage Measurement Error
- Battery Stack Cell Voltage Acquisition Time
- “Hot Plug” Reliability
- Cell Balancing Methods
- Diagnostics and Safety
- Ultra-low Quiescent Current

Renesas Battery Cell Management Solutions
- Battery Monitoring IC Market Prediction
- Major Requirements
- Roadmap of Battery Monitor IC for HEV/EV
- The Renesas Advantage in BMS Applications
Introduction to Battery Cell Management
The Big Deal about Lithium Ion Battery Packs

- Charge balance is the crucial performance characteristic of the battery pack
  - Charge imbalance limits the total usable capacity of the battery pack
    - Pack performs to the “lowest common denominator”
  - Charge imbalance can be caused by many factors
    - Variations in manufacturing process
    - Operating conditions, i.e. temperature, etc.
    - Age

- Battery manufacturers take great care to provide a well-balanced battery
  - Cells sorted by manufacturer to reduce variability amongst the cells
    - capacity and internal resistance
    - adds cost to the manufacturing of the battery pack
  - Battery packs still require careful monitoring and balancing to optimize performance due to mismatch reasons noted above
    - Improper balance can lead to over-charging or under-charging, eventually damaging the battery cells
State of Charge (SOC) vs. State of Health (SOH)

State of Charge

- Measure of the capacity of each cell or entire pack
  - Measured in %
  - Equivalent to a fuel gauge

- Cannot be determined by direct measurement

- Absolute Measure
  - Reflects an objective measure of charge remaining in the cell
  - Many methods generally accepted across the industry

State of Health

- Measure of the capability of the pack compared to original specifications
  - Measured in %
  - Figure of merit

- Cannot be determined by direct measurement

- Relative Measure
  - Subjective measure comparing present state to original state
  - No market agreement for determination
Methods for Determining State of Charge (SOC)

- **Direct**
  - Discharge battery at a constant rate
  - Not practical due to changing load current, discharging load current decrease versus age and others

- **Internal Impedance Measurement**
  - Not widely used due to complex measurement and data interpretation

- **Specific Gravity**
  - Measuring the weight of the active chemicals (as in lead-acid)
  - Not suitable to other chemical compositions such as lithium-ion
**Methods for Determining State of Charge (SOC)**

- **Coulomb Counting**
  - Measures current into or from a cell integrated over time
  - Most accurate method for determining SOC, but cannot predict voltage degradation

- **Voltage-based**
  - Simple and widely used, but varies with temperature, discharge rate, etc.
    - Lead-acid voltage is linear with charge whereas lithium ion is very nonlinear

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**Image Descriptions**

- **Open circuit voltage vs. Residual capacity 25°C**
  - Graph showing the relationship between open circuit voltage and residual capacity for both lead-acid and lithium ion batteries at 25°C.

- **Discharge characteristics of 100Ah Li-ion cell.**
  - Graph showing discharge characteristics for a 100Ah lithium ion cell at various temperatures (35°C to -10°C).
Balancing Individual Cells to Optimize SOC

- Passive balancing is used to adjust the state of charge (SOC) to optimize the ability for the battery to provide maximum energy
  - Each cell of the pack (even the lowest) must be allowed to fully charge and discharge to maximum the battery capacity

- Passive balance bleeds charge from higher charged cells
  - Cells are discharged to the lowest common denominator
    - Cell with the lowest capacity sets the bar
  - Power dissipated in heat via an external resistor
  - Lowers the overall efficiency of the battery pack

- Balancing current depends upon many factors
  - Capacity of the cell
  - Time allowed for balancing
  - Expected amount on imbalance
A Typical Cell Balancing Algorithm

- Balancing a group of 6-12 cells begins with a charging cycle
  - Voltage on each cell is measured and stored
  - Lowest cell is identified
  - Charging begins

- Charging cycle ends when one cell reaches the maximum target voltage (or an internal timer expires)
  - Voltage on each cell is again measured and stored

- If the cell with the highest voltage is not the cell that started with the lowest voltage, the cells must be balanced
  - Cell with the lowest voltage becomes the balanced-voltage target value
  - Remaining cells are discharged until they reach the balanced-voltage target value

- The cycle is then repeated as necessary
Example of Battery Management System

- Single battery monitor IC can monitor 6 to 12 cells in series
- Multiple battery monitor ICs are cascaded in series
  - Single MCU can manage the entire string with high-speed serial communications interface
  - Battery Management Unit manages the oversight of the system

**Battery Management Unit (BMU)**

- **MCU (V850E2/SH-2A)**
  - CPU
  - RAM
  - CAN
  - CAN
  - CAN
  - ADC

- **MCU (RL78)**
  - CPU
  - RAM
  - ROM

**Cell Monitor Unit (CMU)**

- **BMIC* (R2A200xx)**
  - SPI
  - ADC
  - SPI

- Total ~96 cells
- Li-ion Battery cells
- 6~12cells

**Example of Battery Management System**

- Single battery monitor IC can monitor 6 to 12 cells in series
- Multiple battery monitor ICs are cascaded in series
  - Single MCU can manage the entire string with high-speed serial communications interface
  - Battery Management Unit manages the oversight of the system
Battery Management System Architectures

- Centralized vs Distributed Cell Management Unit (CMU)

**Centralized CMU**

**Distributed CMU**

Pass-through Daisy-Chain Return

Fully-buffered Daisy-Chain Return
Battery Cell Management: Features of Merit
ADC Cell Voltage Measurement Error

- Voltage changes are relatively small over the discharge curve and vary with load and temperature.

- Voltage measurements are made in a harsh automotive environment:
  - Load current transients
  - Electromagnetic interference
  - Voltage transients
  - High common-mode voltages

High accuracy allows for accurate SOC calculations, allowing the battery management system to make full use of the available battery capacity.
Battery Stack Cell Voltage Acquisition Time

- SOC algorithms require a periodic, synchronous sample of all the cells in the battery pack.

- The total acquisition time depends on a number of factors:
  - BMS communications architecture
    - Distributed vs. Centralized
  - ADC conversion time
    - Delta-sigma vs. Successive Approximation
  - Number of cells

- Cells must be simultaneously sampled for the most accurate calculation.

- Customers generally require a total acquisition time between 5-10 milliseconds.
“Hot Plug” Reliability

- During vehicle assembly, cell connections from the battery pack to the CMU are made at random, known as “hot plug”
  - Not only between different BMICs in a string, but among any 12 cells of any single BMIC within the string!
- The BMIC must meet stringent voltage and transient requirements in worst case connection scenarios due to sneak paths from external components

Sample of actual OEM test scenarios

- Highest cell on highest IC (e.g. cell 96) is connected first followed by ½ the stack voltage (e.g. cell 48 to system ground), creating a high voltage stress through input filter components and inter-device protection discrete components
- Lowest cell on highest IC (e.g. cell 85) is connected first followed by ½ the stack voltage (cell 48 to system ground), creating a high voltage stress through cell balancing components and inter-device protection discrete components
- Next-to-highest cell on highest IC (e.g. cell 95) is connected first followed by ½ the stack voltage (cell 48 to system ground), creating a high voltage stress through input filter components and inter-device protection discrete components
Cell Balancing Methods

**Passive**

- **Flyback**

**Active**

- **Buck**
- **Buck-boost**

**Efficiency**

**Cost**
Diagnostics and Safety

- **Cell over-voltage and under-voltage**
  - Provides fault monitoring to detect ADC fault on voltage measurement
  - Can be combined within the BMIC or in other cases is a stand-alone parallel monitor device (without cell balancing)
  - Assists with diagnosis of open cell input

- **Loss of cell input voltage (open-circuit)**
  - Open cell voltage input could provide valid A/D result
  - IC must successfully distinguish open-circuit from a dead cell
    - Can’t simply pull up or down on the input

- **Cell balance switch status**
  - Must verify the on/off capability of the switch

- **Loss of VCC or ground**
  - Operation is still possible based upon the presence of other cell inputs
Ultra-low Quiescent Current

- **Quiescent current**
  - Battery monitor IC draws current from battery cells
  - Vehicle is off most of its life, resulting in a constant discharge load
  - Minimizing leakage is paramount!

- **Quiescent current variability among BMICs in a string**
  - Each BMIC draws current from the cells it monitors
  - Lithium-Ion battery packs are most reliable if the charge and discharge cycles are identical
  - Customers require a balanced load drawn by all the BMICs in the stack
    - Results in a very tight distribution requirement!
Renesas Battery Cell Management Solutions
Roadmap of Battery Monitor IC for HEV/EV

High Speed

- R2A20027FP
  - 6 to 12 cell
  - 12-bit SAR ADC
  - +/- 4 mV total error
  - 100 us/96-cell conversion
  - Passive balancing
  - Differential SPI I/F

Higher Accuracy

- R2A20028FP
  - 6 to 12 cell
  - 12-bit Delta-sigma ADC
  - +/- 2.5 mV total error
  - 5 ms/96-cell conversion
  - Passive balancing
  - Differential SPI I/F

Under Development

- R2A200yy
  - 6 to 12 cell
  - Next Generation ADC
  - < +/- 2 mV total error
  - < 100 us/96-cell conversion
  - Active/Passive balancing
  - High speed communications
  - Integrated digital isolation

Next Generation, Under Consideration

2012

Differentiating product features
Products In Development: R2A20027(28)

- Support for 6 to 12 Cells, up to 80 V
- Low A/D Measurement Error
  - R2A20027: +/- 4 mV\(^1\)
  - R2A20028: +/- 2.5 mV\(^1\)
- High-speed Conversion
  - R2A20027: 100 us\(^2\)
  - R2A20028: 5 ms\(^2\)
- Built-in Cell Balancing MOSFETs for reduced part count and smallest PCB footprint
  - 100 mA max
- Built-in Over/Under voltage detection function
- Differential SPI for Robust Communications
  - CRC>10
- Extensive diagnosis & detection functions to help enable ISO26262 compliance

\(^1\) Ta = 25 C  \(^2\) 12 cells
Cell Balancing Methods for R2A20027(28)

- **Type-A**: Separated Balance & Measurement paths
- **Type-B**: Common Balance & Measurement paths
- **Type-C**: Isolated Balancing MOSFET

Voltage Measurement Path
Balancing Current Path
## Product Lineup for an Optimal Solution

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<th>Cell Balancing Option</th>
<th>Packaging</th>
<th>ADC Option</th>
<th>Part Numbers</th>
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<tbody>
<tr>
<td><strong>Type-A</strong></td>
<td>![64-pin LQFP Diagram]</td>
<td>![12-bit SAR ADC]</td>
<td>![R2A20027AFP]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>![12-bit DS ADC]</td>
<td>![R2A20027BFP]</td>
</tr>
<tr>
<td><strong>Type-B</strong></td>
<td>![64-pin LQFP Diagram]</td>
<td>![12-bit SAR ADC]</td>
<td>![R2A20027CFP]</td>
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<td>![12-bit DS ADC]</td>
<td>![R2A20027DFP]</td>
</tr>
<tr>
<td><strong>Type-C</strong></td>
<td>![80-pin LQFP Diagram]</td>
<td>![12-bit SAR ADC]</td>
<td>![R2A20027EFP]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>![12-bit DS ADC]</td>
<td>![R2A20027FFP]</td>
</tr>
</tbody>
</table>

**Packaging**
- 64-pin LQFP
- 80-pin LQFP

**ADC Option**
- 12-bit SAR ADC
- 12-bit DS ADC

**Part Numbers**
- R2A20027AFP
- R2A20027BFP
- R2A20027CFP
- R2A20027DFP
- R2A20027EFP
- R2A20027FFP
- R2A20028AFP
- R2A20028BFP
- R2A20028CFP
- R2A20028DFP
- R2A20028EFP
- R2A20028FFP
Reference Platform

- **Cell Monitor Unit (CMU) Board**
  - R2A20027/28 BMIC\(^1\) and 78K0R/Fx3
  - Isolated connection to 78K0R/Fx3 board
  - SPI connector for daisy-chain connection to a second R2A20027/28 board

- **Load/Battery Module**
  - Design under consideration

- **Battery Management Unit (BMU) Board**
  - V850E2/Fx4 MCU
  - CAN connector for connection to the CMU
  - Cell voltage display
  - Battery charge switch

- **Battery Charger Unit**
  - Control signals available from BMU board for battery charger control

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\(^1\) Battery Management IC
The Renesas Advantage in BMS Applications

- Delivering automotive robustness and consumer market leadership in lithium-ion battery cell management applications
- Offering voltage measurement options to meet evolving system architecture requirements
  - SAR for faster stack sampling and low A/D error
  - Delta-sigma for even more accurate A/D performance in less time-critical implementations
- Providing various cell-balancing options to provide greatest flexibility in passive cell balancing systems available on the market
- Integrating passive balancing switches to eliminate dozens of external components and reduce PCB footprint for the lowest system cost
- Utilizing differential SPI to enable a robust, noise-immune communication channel throughout the stack
- Supporting a full suite of built-in diagnostic functions to enable ISO26262 compliance
Questions?
‘Enabling The Smart Society’

Challenge:
“The electrification of the automobile brings substantial challenges in it’s goal to contribute to the establishment of the Smart Society as a robust, efficient yet economical alternative to fossil-fuel-derived energy. Among the greatest challenges lies within the management of the single most expensive component of the electrified vehicle, the battery.”

Solution:

“Renesas battery management solutions couple high-accuracy performance with exhaustive protection and flexible architectures for optimal battery management systems.”

Do you agree that we accomplished the above statement?
Automotive Analog and Mixed-Signal Product Experience

Black - ASCPs (Application Specific Custom Product)
Blue-ASSPs (Application Specific Standard Product)

Engine Control
- CNG Direct Injection
- MAP Sensor
- Crank Sensor
- Coolant Temp Sensor

Dashboard
- Gauge Driver
- HVAC Control

Body
- Seat Position Control
- Keyless Entry
- HID Control
- Rain/Light Sensor
- Sunroof
- Window Lifter
- Steering Switch
- Power Management

Battery Management
- Li-Ion Battery Monitor
- Battery Sensor

Navigation
- Angular Sensor
- Velocity Sensor
- Audio Amp

Safety
- Occupant Sensor
- Rollover Sensor
- Squib Driver
- Satellite Sensor

Brake
- Wheel Speed Sensor
- Pre-driver
- Steering Angle Sensor
- Steering Torque Sensor

Dashboard

Navigation

Safety

Brake
R2A20028FP (Delta-sigma ADC)

- High voltage: 80V max (available for 12 cells)
- Low measurement error: +/- 2.5mV @ 25degC
- High speed measurement: 10ms max / 12 cells
- Reduced external parts:
  - Built-in cell balancing MOSFET (100mA max.)
  - Built-in Over/Under voltage detection function
- High reliability I/F: Differential SPI, CRC >= 10
- Various diagnosis/detection functions to be compliant with ISO26262

**Parameter** | **Target Spec.**
--- | ---
Monitoring cell number | 6 to 12 cells (VCC > 10V)
IC addressing | External pin or Command
Maximum stackable number | External pin: 8ICs, Command: 16ICs (TBD)
Power supply voltage | 10 to 60V (Max. rating voltage: 80V)
Cell voltage range | 0 to 5.0V (VCC > 10V)
Operating temperature range | -40 to 105degC
ADC | 12-bit resolution Delta-sigma ADC
Sampling clock frequency | 1MHz
Series regulator | VREG1: 5.0V typ. (for internal communication circuit)
          | VREG2: 3.3V typ. (for internal logic circuit)
Cell voltage measurement error | +/- 2.5mV (25degC), +/- 5mV (-40 to 105degC)
ADC conversion time | 5ms max / 12 cells
Cell voltage measurement speed | 10ms max / 12 cells (ADC + Communication)
Power consumption | 1.8mA max. (ADC operating) * excluding communication current
          | 225uA max. (Standby mode)
          | 10uA max. (Deep sleep mode) (TBD)
Cell balancing | Method
          | Type-A: Not adjacent 6 cells can discharge @ 100mA max
          | Type-B: All adjacent 12 cells can discharge @ 70mA max
          | Type-C: All adjacent 12 cells can discharge @ 70mA max
Timer | Built-in OFF timer (TBD)
Serial interface | Differential SPI (IC-IC: Current mode, MCU-IC: Voltage mode)
          | * MCU-IC: Differential or Single-end selectable
Clock frequency | 1MHz max.
Interrupt output | 2ch (CRC error, ADC completion, Initialization completion)
Ext. temp. sensor (For thermistor) | 2ch (IC addressing: External Pin)
          | 4ch (IC addressing: Command)
Chip temp. sensor | 1ch
Self diagnosis function | ADC data register diagnosis and write data verify
          | Communication diagnosis (CRC, frame error)
Detection function for diagnosis | Initialization diagnosis
          | ADC diagnosis
          | Cell balance diagnosis (Cell balance SW monitor)
          | Data register diagnosis (User test mode)
          | Open-wire diagnosis
          | OCO diagnosis (OCO CLK counter)
          | Battery over-voltage/Under-voltage detection
          | IC address diagnosis
Package | Cell balancing Type-A, B: 64-pin LQFP
          | Cell balancing Type-C: 80-pin LQFP

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**Block Diagram**

- 12-bit Δ-σ ADC
- Control register
- SPI
- Serial interface (Differential SPI)
- Cell balancing (Type-A, B, C)
- Built-in cell balancing MOSFET (100mA max.)
- Built-in Over/Under voltage detection function

**Supported Features**

- High voltage: 80V max (available for 12 cells)
- Low measurement error: +/- 2.5mV @ 25degC
- High speed measurement: 10ms max / 12 cells
- Reduced external parts:
  - Built-in cell balancing MOSFET (100mA max.)
  - Built-in Over/Under voltage detection function
- High reliability I/F: Differential SPI, CRC >= 10
- Various diagnosis/detection functions to be compliant with ISO26262
R2A20027FP (SAR ADC)

- High voltage: 80Vmax (available for 12cells)
- Low measurement error: +/-4mV @25degC
- High speed conversion: 100us max/12cell
- Reduced external parts:
  - Built-in cell balancing MOSFET (100mA max.)
  - Built-in Over/Under voltage detection function
- High reliability I/F: Differential SPI, CRC>=10
- Various diagnosis/detection functions to be compliant with ISO26262

Parameter | Target Spec.
---|---
Monitoring cell number | 6 to 12cells (VCC>10V)
IC addressing | External pin or Command
Maximum stackable number | External pin : 8ICs, Command : 16ICs (TBD)
Power supply voltage | 10 to 60V (Max. rating voltage: 80V)
Cell voltage range | 0 to 5.0V (VCC>10V)
Operating temperature range | -40 to 105degC
ADC | 12 to 14bit resolution SAR ADC
Series regulator | VREG1 : 5.0V typ. (for internal communication circuit)
| VREG2 : 3.3V typ. (for internal logic circuit)
Cell voltage measurement error | +/-4mV (25degC), +/-8mV (-40 to 105degC)
ADC conversion time | 100us max./12cells
Cell voltage measurement speed | 5ms max./12cells (ADC+Communication)
Power consumption | 1.8mA max. (ADC operating) * excluding communication current
| 225uA max. (Standby mode)
| 10uA max. (Deep sleep mode) (TBD)
Cell balancing Method | Type-A: Not adjacent 6 cells can discharge @100mA max
| Type-B: All adjacent 12cells can discharge @70mA max
| Type-C: All adjacent 12cells can discharge @70mA max
Timer | Built-in OFF timer (TBD)
Serial interface Differential SPI (IC-IC: Current mode, MCU-IC: Voltage mode)
  * MCU to IC: Differential or Single-end selectable
Clock frequency | 1MHz max.
Interrupt output | 2ch (CRC error, ADC completion, Initialization completion)
Ext. temp. sensor (For thermistor) | 2ch (IC addressing: External Pin)
| 4ch (IC addressing: Command)
Chip temp. sensor | 1ch
Self diagnosis function | ADC data register diagnosis and write data verify
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Package | Cell balancing Type-A, B : 64pin LQFP
| Cell balancing Type-C : 80pin LQFP
## Cell Balancing Methods

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<th>Type-C</th>
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<td>Discharge path/Measurement path</td>
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<td>MOSFET Drain/Source</td>
</tr>
<tr>
<td>Separate type</td>
<td>Common type</td>
<td>Separated type</td>
</tr>
</tbody>
</table>

### Circuit diagram

- **Type-A**: Discharge path/Measurement path (Separate type)
- **Type-B**: Discharge path/Measurement path (Common type)
- **Type-C**: MOSFET Drain/Source (Separated type)

### Maximum discharge cell (current)
- **Type-A**: Non-adjacent 6 cells can discharge simultaneously, (100 mA max)
- **Type-B**: All adjacent 12 cells can discharge simultaneously, (70 mA max)
- **Type-C**: All adjacent 12 cells can discharge simultaneously, (70 mA max)

### Measurement During cell balancing
- **Possible**
- **Impossible to obtain high-accuracy measurement**
- **Possible**

### Filtering circuit design
- **Easy**
- **Complicated (Difficult to consist with discharge current setting)**
- **Easy**

### External MOSFET
- Drive voltage will be about BCx/2 (Need low voltage drive MOSFET)
- Drive voltage will be about BCx
- Drive voltage will be about BCx

### Package
- 64 pin-LQFP
- 64 pin-LQFP
- 80 pin-LQFP
Product Lineup for Solution Optimization

- Design options based on a common set of core design features results in a broad product offering
- Choices provided for choosing ADC type, cell-balancing, thermistor inputs and address methods

<table>
<thead>
<tr>
<th>Parts No.</th>
<th>ADC Type</th>
<th>Cell balancing method</th>
<th>Thermistor I/F</th>
<th>Addressing Method</th>
<th>Assigned pin count</th>
<th>Package</th>
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<tbody>
<tr>
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<td>SAR</td>
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