ATLAS Carleton

Probing of ABCStar Readout ASICs Through a Semiconductor Test Industry Partnership for use in the ATLAS ITk Strips Tracker

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CAP Congress - 2023

DA-INTEGRATED
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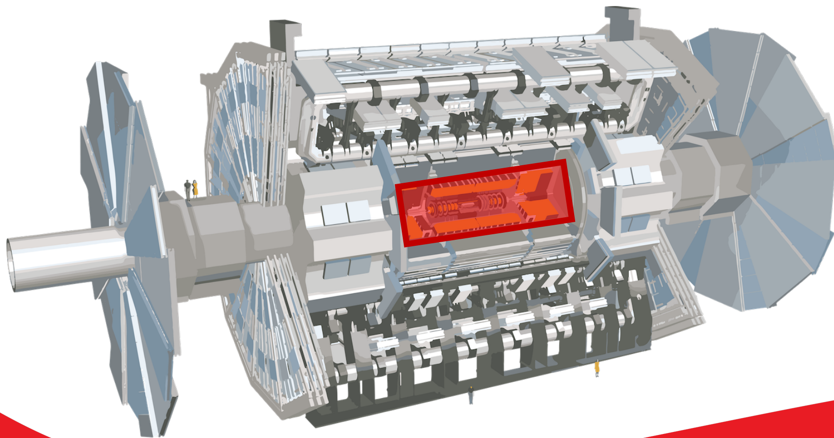
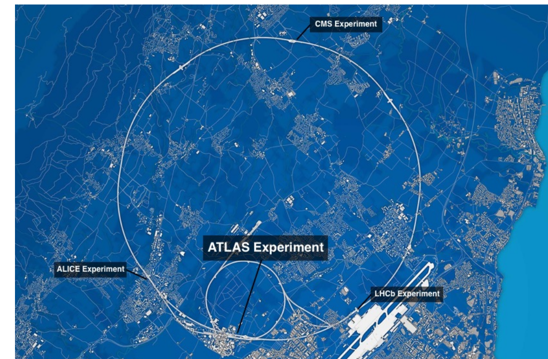
Carleton University
Department of Physics

The LHC and ATLAS

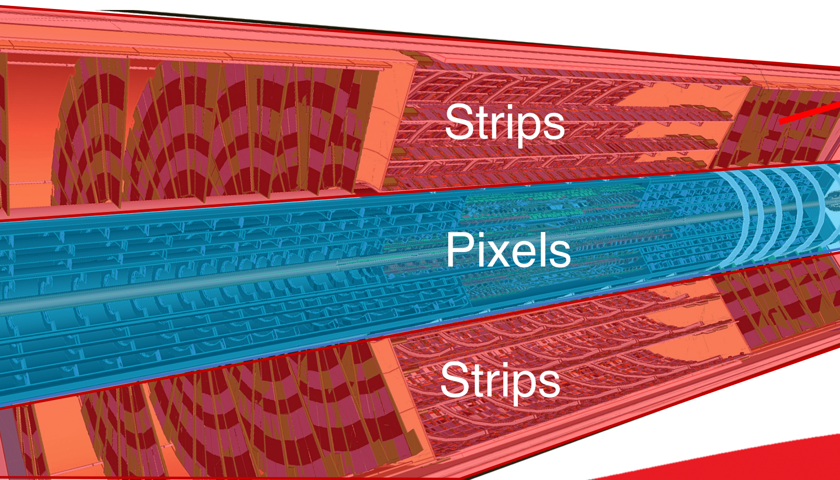
- The Large Hadron Collider (LHC) is the world's largest particle collider
  - Protons accelerated around 27 km ring and collided at center of mass energy of 13.6 TeV
- ATLAS is the largest general-purpose detector on the LHC
  - Helped discover the Higgs boson in 2012
  - Cylindrical detector consisting of many subsystems wrapped in layers
- ATLAS is currently collecting data during LHC Run 3

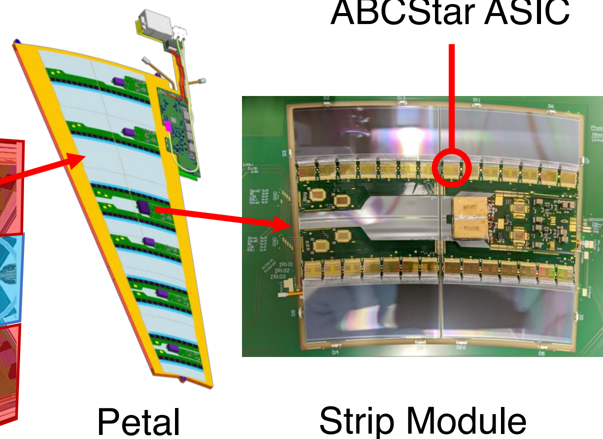




New Inner Tracker (ITk) Upgrade

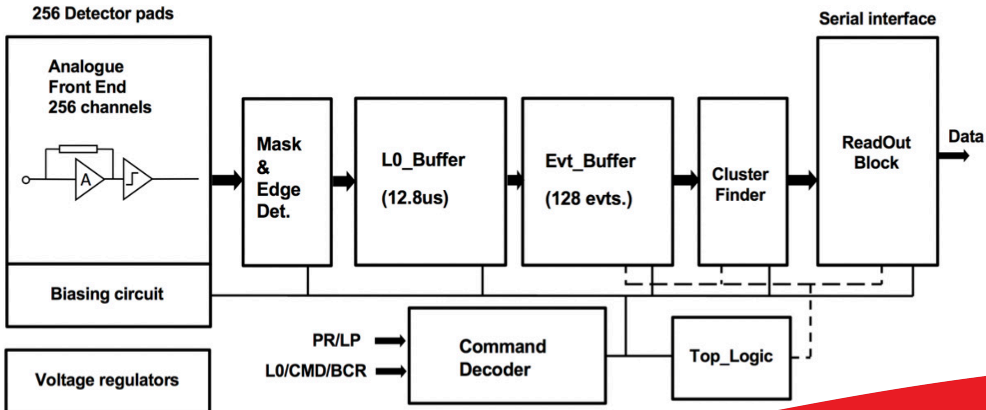
- The LHC is undergoing upgrades to become the High Luminosity LHC (HL-LHC) beginning in 2026
- ITk will replace the current ATLAS Inner Detector
  - Inner Detector is nearing end of life
  - HL-LHC will have over 5 times more collisions than the LHC
- ITk will be an all-silicon detector
  - Consists of pixel and strip subsystem



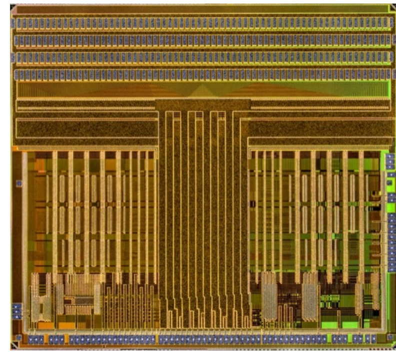


ABCStar ASIC

- ATLAS Binary Chip – Star Version (ABCStar) is the readout ASIC for the ITk strip sensors
  - 8.087 mm x 7.150 mm
  - 130 nm CMOS technology
  - Provides signal processing for 256 silicon strips
  - Binary readout architecture
  - Radiation hard design with triplication
  - Input signals from all 256 channels are amplified, shaped, discriminated then readout



ABCStarV1



ABCStar Wafer Probing

- Analog and digital circuitry of over 350,000 ASICs needs to be thoroughly tested to be used in ITk
  - Half of wafer probing is being done at Rutherford Appleton Laboratories (RAL) with custom equipment in research setting
  - Carleton partnered with DA-Integrated to probe other half of wafers
- DA-Integrated is a global provider of integrated circuit development, production testing and custom ASIC services
  - Located ~25-minute drive from Carleton University
  - Capability to test over 1 million parts on site in a year
  - No custom hardware was needed to interface with ABCStar wafers
  - Voltages and frequencies were easily attainable on their testers
- Worked with test engineers at DA-Integrated to develop test routine for ABCStar using standard industry probing equipment
  - Majority of test implementation for final version of ABCStar was done remotely between DA-Integrated and Carleton

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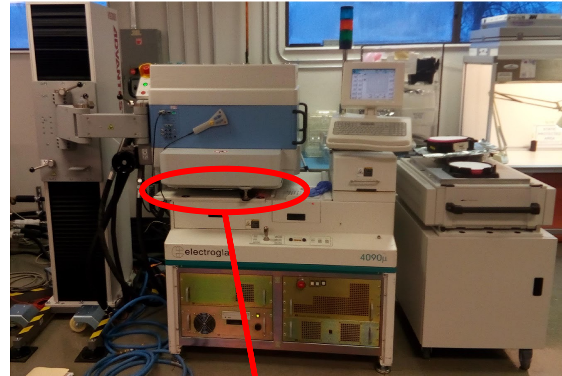
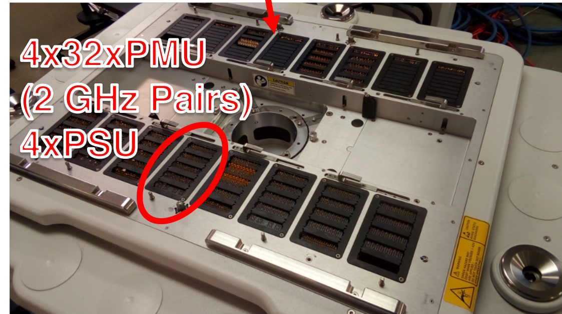
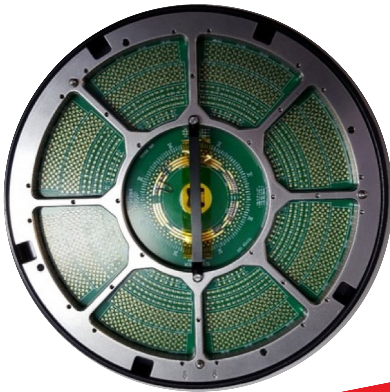
DA-Integrated Wafer Testing System

- Electroglas 4090μ and TEL probers
  - Automated wafer swapping and alignment with up to 25 wafers
  - Programmable power supplies with readout (PSUs)
  - Parametric measurement units (PMUs) to source/sink and measure any voltage or current on pads
- Tests driven by C++ code
- "Shmoo" analysis capabilities

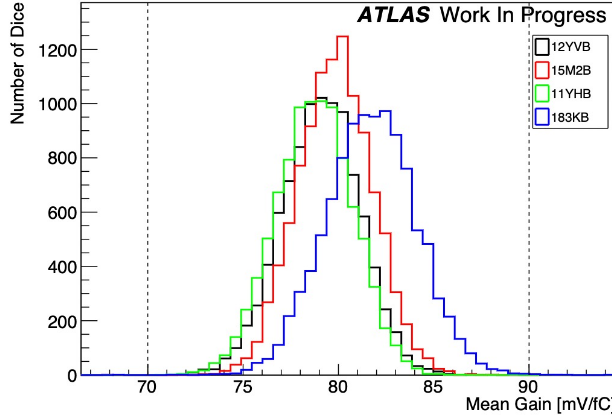




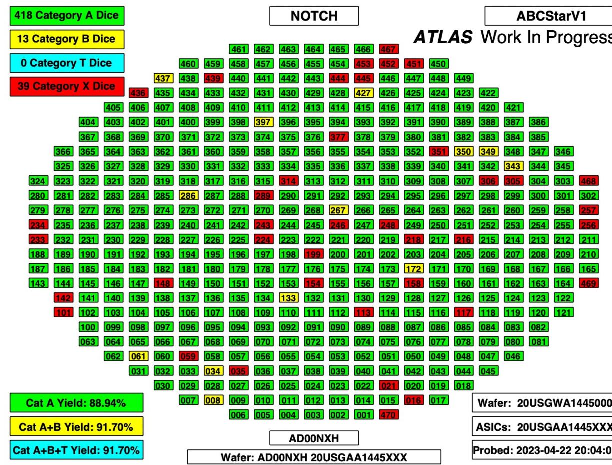


Test Results

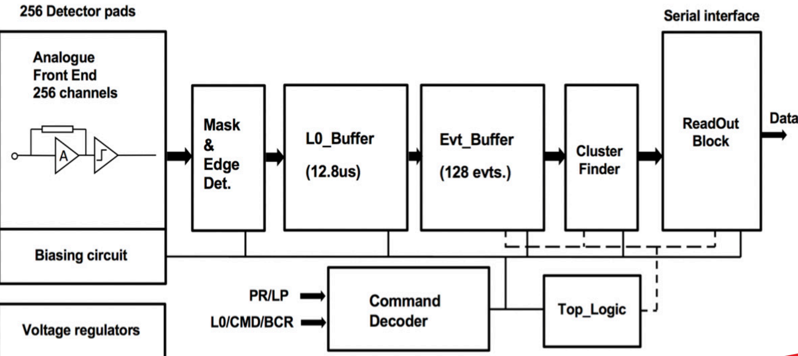
- ABCStar test flow at DA-Integrated
  - Measure power supplies as ASIC functionality is brought up in stages
  - Verify communication with the chip
  - Tune chip to desired voltage
  - Burn eFuses for chip identification
  - Tune internal DACs
  - Measure gain and noise from all 256 channels
  - Test the digital logic of the chip



Mean gain per ASIC across four different lots of wafers



Wafer map showing passing (A), marginal (B) and failing (X) ASICs

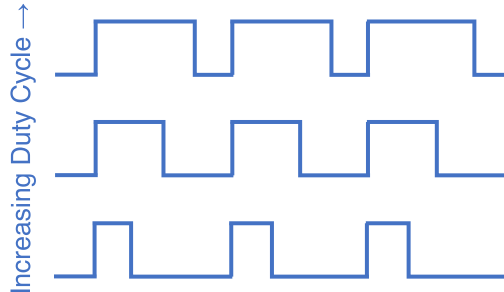


Digital Tests

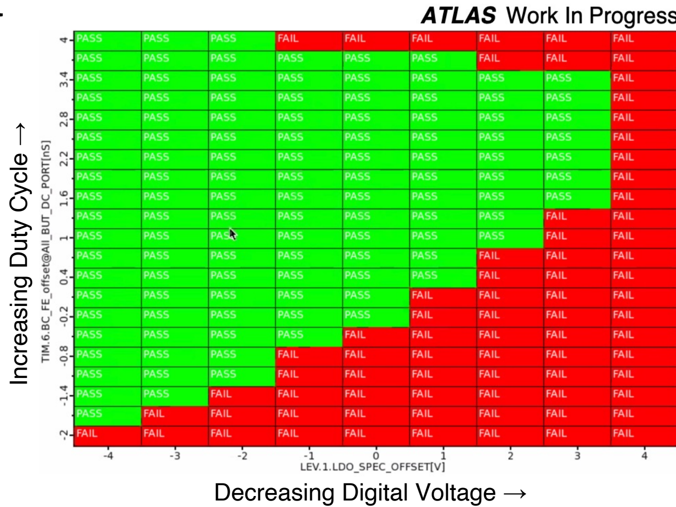
- Tests were developed by engineers at CERN to virtually test digital logic on a simulation of the ABCStar
  - Used Cadence Xcelium software to generate files containing inputs to chip and expected output from chip for each digital test
  - Engineers at DA-Integrated converted these files into a format for probing on physical ABCStar chips
- These tests were designed to run on a simulation of ABCStar, not a physical chip
  - Needed to adjust tests that accessed internal properties of the chip not available to the tester
- Wanted ability to run digital tests at different voltages
  - Voltage of chip was hard coded in test
  - Developed code to dynamically change the bit stream sent to each ASIC to change the voltage settings

SRAM Hit Loss

- Discovered that ABCStar ASICs could experience hit loss if digital voltage or duty cycle was too low during probing
  - When reading out physics data some hits were missing in readout compared to expected good stream for “A02” digital test
  - Hit loss = missing physics data
  - Localized the issue to bit flips in the on-chip SRAMs
- Needed to determine relationship between digital supply voltage, duty cycle and SRAM hit loss
  - DA-Integrated has precise control over clock frequencies and edge relationships
  - Prober can quickly generate shmoo plots



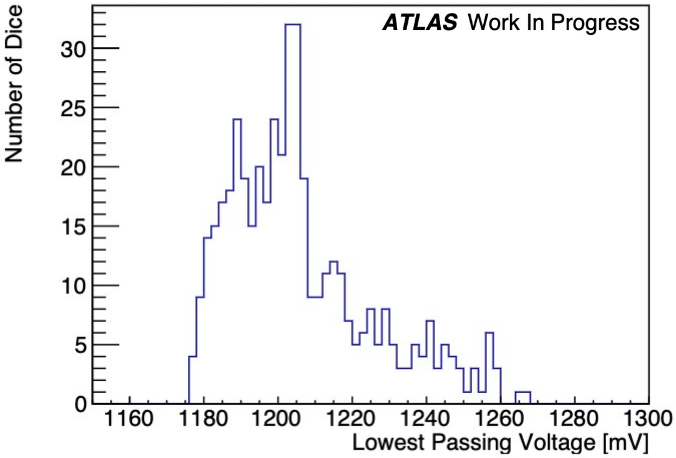
Duty cycle is ratio of high time to low time



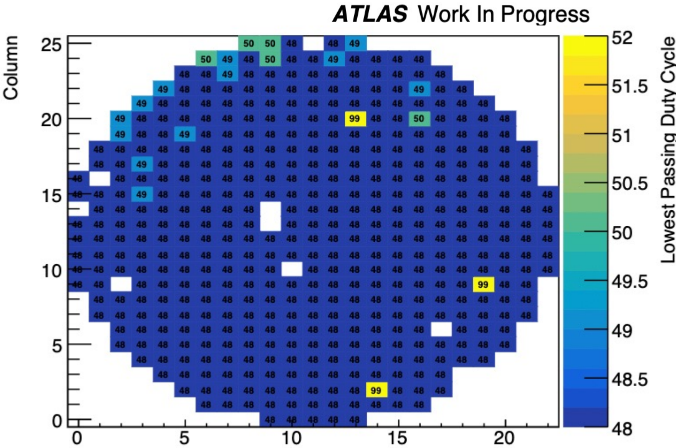
Shmoo plot showing pass/fail result for A02 test with different supplied duty cycles and voltages for an ASIC

SRAM Investigation

- Needed to determine criteria for passing ABCStar chips to avoid hit loss in ITk while maintaining high wafer yield
  - Maximum operating voltage is limited by supply voltage
  - Duty cycle to ABCStar is set by its control chip
- Performed SRAM test at different voltages and duty cycles across multiple wafers
  - Decided that ASICs must have zero hit loss with 1.25 V digital voltage and 49/51 duty cycle



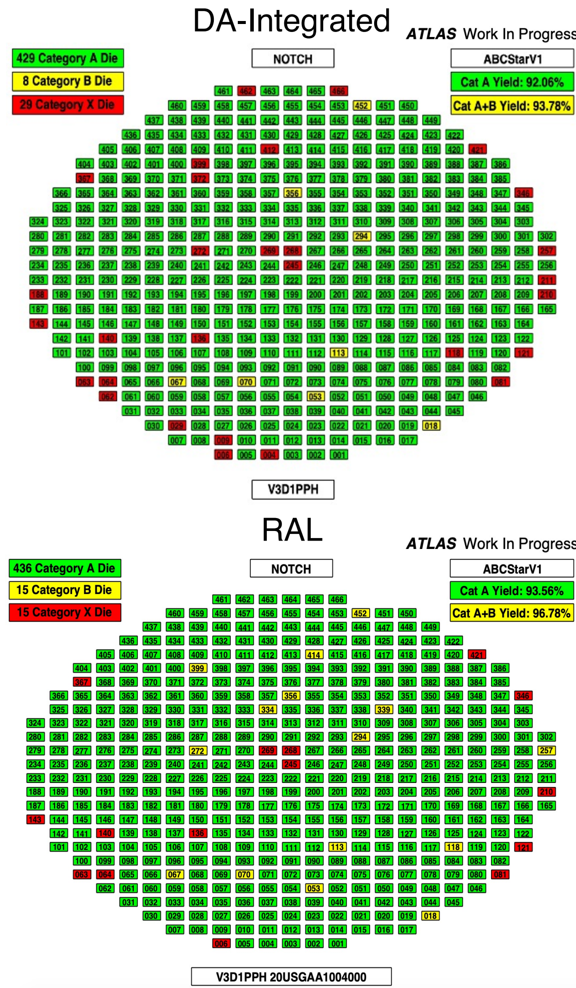
Lowest voltage where A02 (SRAM test) passes for a wafer



Wafer map with lowest supplied duty cycle for a passing SRAM test

Site Cross-Check

- Two wafers were probed at RAL and DA-Integrated for site verification
- Die classification was compared to ensure that results are consistent between sites
  - **99.8% agreement** after accounting for differences in test coverage and limits (have since been rectified)
  - Remaining 2 dice were on the edge of a test limit
  - Second cross-check occurring soon
- DA-Integrated achieved the same test coverage with better throughput
  - DA: ~2 hours/wafer, automated wafer swapping (probe lot in weekend)
  - RAL: ~4 hours/wafer, manual loading (average 2 wafers per day)



Conclusion

- Partnered with a commercial ASIC testing company to probe ABCStar ASICs for the ATLAS ITk upgrade
  - Currently in production probing with over one third of ASICs probed
  - Average yield of 87.4% through production probing

ABCStar	Manufactured	Probed	Diced
Number	269780	143350	62584
%	77.1%	41.0%	20.9%

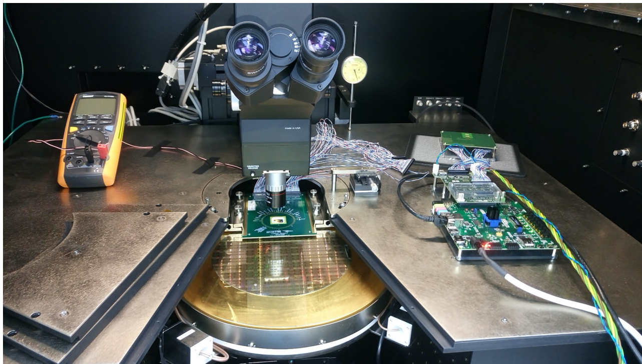
- Overcame methodological differences between industry and research facilities without compromising test coverage
  - Achieved 99.8% consistency in classification between probing sites
- Leveraged probing capabilities at DA-Integrated to investigate ABCStar SRAM behaviour
- Opened the door for future collaboration with commercial ASIC testing vendors in high energy physics experiments
  - This could be the future for large scale physics experiments

Backup

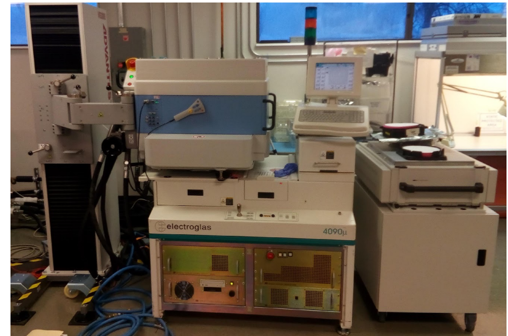
Carleton University | Department of Physics

Probing: Commercial vs Research

- RAL (Research)
  - Custom probing setup integrated with custom software
  - Can probe a wafer of 470 ASICs in ~4 hours
  - Manual wafer swapping (10-15 min)
  - Unlimited access to probing setup allowing for quicker debugging and R&D when necessary



- DA-Integrated (Commercial)
  - Industry standard wafer probing equipment
  - Can probe a wafer of 470 ASICs in ~2 hours
  - Automated wafer swapping, can probe 25 wafers over weekend
  - Limited time windows for R&D
  - Work with test engineers to implement probing tests



ABCStar Production Status

- Currently in production probing phase

ABCStar	Manufactured	Probed	Diced
Number	269780	143350	62584
%	77.1%	41.0%	20.9%

Foundry lot	Probing standard used	Num wafers	Wafers probed	Wafers still to probe	% yield cat A
0XDXB00000	Production	24	20	4	**80.5%**
0ZPRB00000	Production	21	21	0	**88.1%**
107RB00000	Production	25	2	23	**71.5%**
110YB00000	Production	22	22	0	**89.9%**
11YFB00000	Production	19	19	0	**86.5%**
11YGB00000	Production	23	23	0	**91.8%**
11YHB00000	Production	22	0	22	
12YVB00000	Production	22	22	0	**85.6%**
144YB00000	Production	23	0	23	
15M2B00000	Production	23	23	0	**90.9%**
17S2B00000	Production	25	25	0	**85.7%**
183KB00000	Production	23	0	23	
2YEWB020000	Production	2	2	0	**80.3%**
2YRKB00000	Production	25	2	23	**90.5%**
2ZKTB00000	Production	25	0	25	
3024B00000	Production	24	2	22	**87.8%**
31VWB00000	Production	25	0	25	
33YXB00000	Production	25	0	25	
34Q7B00000	Production	25	2	23	**89.6%**
35C1B00000	Production	25	0	25	
361CB00000	Production	24	2	22	**92.0%**