
Image by Arnon Parnnao. Adobe Stock.

Photonic Integrated Devices

Manufacturing Workforce Preparation Assessment Report

Middle Skilled Technicians

Conducted by the Conducere-MIT Collaboratory

Juliet Aiken, PhD; Autumn Fedewa, Taylor Jordan

Conducere Consulting

Frank Field, PhD; Randolph Kirchain, PhD; Elizabeth Moore, PhD; Beth Unger, PhD

Massachusetts Institute of Technology (MIT) Materials Systems Laboratory

Anuradha Argarwal, PhD

Massachusetts Institute of Technology (MIT) Microphotonics Center and Materials Research Laboratory

Table of Contents

Executive Summary

The Conducere-MIT Collaboratory conducted a Manufacturing Workforce Preparation assessment (MWP) for photonic integrated devices, particularly bio-photonic devices. Leveraging data from O*NET and expert interviews, the team identified the need for two manufacturing technician positions, the Photonic Integrated Circuit Technician and the Functionalization Technician. The team identified tasks, skills, and competencies that are critical and needed at entry for manufacturing technicians producing photonic integrated devices. While tasks between these positions are expected to vary somewhat, the skills and competencies needed to be successful are not expected to vary much. Additionally, needed skills and competencies will likely differ for technicians working predominantly with automated equipment and technologists who conduct their work more manually. Much of what technicians need to be able to do will be learned on the job.

This report first shares what photonic integrated devices are and summarizes our findings relevant to the market for this emerging technology. The report then details role, task, skill, and competency findings for the technician positions, and provides insight into equipment, education, recruiting, hiring, and training.

Sensor Devices

A sensor is a device that is used to convert some characteristic of the sensor's physical environment into a measurable signal that can be processed by other devices.

For example, a mercury thermometer is a sensor device that detects changes in temperature. It "works" because mercury (like many other materials) changes its density when its temperature changes. By putting a fixed quantity of mercury in a tubular cavity whose size is calibrated and properly configured, the height of the column of mercury in the tube will correspond to a known temperature. The thermometer is the sensor and the height of the tube occupied by the mercury is the signal that the user's eye converts to temperature by reading the number etched into the glass tube.

There are many kinds of sensors, but all share the general characteristic of being a device that, under the influence of a change in environmental conditions, generate a signal that can be interpreted to produce an indication that some environmental condition has changed.

The development of a good sensor, then, depends on the ability to engineer a physical system:

- That is responsive to a change in a particular environmental condition, while being relatively insensitive to all other changes in environmental conditions,
- Whose responsiveness is sufficiently predictable that it can be calibrated against some kind of reference state, and
- Whose response can be converted into a high quality signal that can be used by other systems.

Photonic Sensor Devices

What are photonic sensor devices?

In this sensor scheme, a photonic sensor is a sensor device whose response is a function of changes in light waves. Where a mercury thermometer's response is found in the way that the density of mercury changes with temperature, a photonic sensor device's response is found in the way that light (its intensity, frequency, direction, or phase) can be made to change with changes in the environment. While the change in the density of a material is a relatively simple physical characteristic to build a sensor around, changes in light can be considerably more nuanced, meaning that, while changes in light can be used to detect a much wider range of environmental changes, a considerably more sophisticated infrastructure is required to develop a physical system that can be used to create a sensor device.

The variety of the ways that light is influenced by changes in its environment means that there are a wide range of mechanisms that can underlie the operation of a photonic sensor device. This variety of response mechanisms (as well as the rate at which changes in light can be detected) also means that, with appropriate design and processing, a wide range of physical phenomena can be monitored using photonic sensor devices.

The mechanism employed in the design of photonic integrated devices for chemical and biological environmental conditions typically centers on the way that light travels in a waveguide (Luan, Shoman, Ratner, Cheung, & Chrostowski, 2018). A waveguide is a resonant cavity for electromagnetic radiation with a number of important properties.

A fundamental feature of a waveguide is that the boundary of the waveguide confines the electromagnetic radiation, typically via internal reflection (Steglich et al., 2022). One consequence of this reflection is that a waveguide can only transmit electromagnetic radiation whose wavelengths are compatible with the geometry and material composition of the medium through which the radiation travels.

There is a third factor that constrains the radiation within a waveguide: the physical characteristics of the medium that lies immediately outside the boundary of the waveguide. The reason for this dependence arises from the physics of reflection, the mechanism that confines the radiation to the waveguide. When electromagnetic (EM) radiation is reflected, what happens is that the reflecting material reacts to the incoming radiation in such a way as to produce the apparent reflection.

The mechanism of reflection depends upon the electromagnetic properties of the waveguide material and its design. Because the physics of traveling electromagnetic waves does not allow for discontinuities upon reflection of the wave, the net effect of reflection is that there is a so-called “evanescent field” that is induced by the passage of electromagnetic radiation through a waveguide. This evanescent field is OUTSIDE the waveguide and, importantly for sensor design, changes in the electromagnetic properties of the region on the waveguide boundary CHANGE the evanescent field and, thus, the way that reflection happens INSIDE the waveguide.

The trick, then, to developing an effective photonic sensor is finding the combination of (1) waveguide and associated photonics design, (2) light properties, and (3) surface chemistry of the outside of the waveguide such that a particular chemical (or biochemical) reaction might occur in the presence of the material or organism that we wish to detect that has enough of an effect on the evanescent field to detectably change the light passing through the waveguide. Finally, of course, we will require (4) appropriate detection, signal processing, and interfacing infrastructure so that the sensing. A schematic of an integrated photonic chemical sensor system is below.

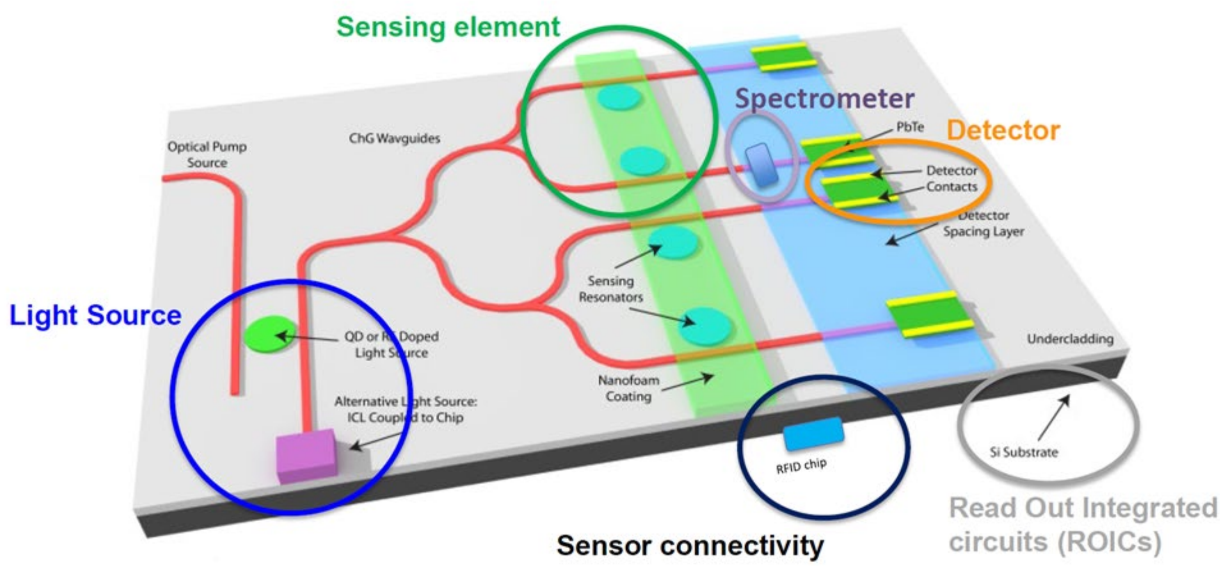

Figure 1. An integrated photonic chemical sensor system where the light source is circled in blue, the sensing element is circled in green, the spectrometer is circled in purple, the detector is circled in orange, the sensor connectivity RFID chip is in dark blue, and the read out integrated circuits is circled in grey. © A. Agarwal, J. Hu, J. Michon, M. Shalaginov 2020

Why are these sensors complex to manufacture?

Two physical features of the photonic devices that have been devised for this kind of sensing are directly related to the manufacturing complexity associated with making these devices. The first of these is that (1) the strength of evanescent fields drops of quickly with distance from the reflecting/resonant surface of the device and the second is that (2) most of these kinds of sensing applications are attempting to detect conditions associated with relatively low concentrations of chemicals or biological agents.

The rapid drop off in field strength means that the active chemical/biological reagent has to be precisely and thinly applied to the surface of the resonant components while the relatively low concentrations of agents to be detected means that relatively large surfaces have to be prepared in order to increase the probability of a measurable reaction in the coating — specifically, a detectable change in the dielectric properties and, thus, the refractive index at the surface of the resonant device.

There are, as a consequence, a variety of photonic systems that are being deployed to create these kinds of sensors. However, the physical features of these sensors lead to incredibly demanding manufacturing, with precision measured in 10s of nanometers.

Manufacturing of silicon devices at this level of precision is not uncommon, but it is extremely demanding (Shahbaz, Butt, & Piramidowicz, 2023). Unlike electronic devices, where feature size influences efficiency and speed, feature sizes in photonics influence the dispersion properties of the photonic device itself (i.e., the color of the light that the device can support/detect) and the way that the light moves through the sensor.

MWP for Photonic Integrated Device Manufacturing Technicians

We conducted a Manufacturing Workforce Preparation (MWP) study following the WRL Workbook to uncover the needs for a technician (middle skilled) workforce manufacturing photonic integrated devices. Below, we provide our findings.

Study Context

An MWP may be funded by an organization specifically to inform their own operations, or by a third-party source to inform the workforce needs for a field as a whole more generally. This MWP was funded by a third-party source.

Team

According to the Workforce Readiness Level Deskbook (Conducere-MIT Collaboratory, 2024), each assessment team should have at least:

> One person familiar with the technology, or parallel products and contributing technologies, and the market;
>
> One person (or a person representing an institution) who has access to academic and industry contacts in the industry, or the industries for PC technologies;
>
> One industrial/organizational (I/O) psychologist (or a similar profession) with a background in job analysis and/or competency modeling; and
>
> One social science researcher with a background in qualitative (interview/focus group) and survey research methodology

The team working on this MWP included five experts located at an academic institution who were familiar with the technology, PC technologies, and the market, and had access to critical contacts for learning about photonic integrated devices. The team also included three I/O psychologists, including one with a background in qualitative, archival, and survey research methodology. The biographies for the team members working on this MWP are included in Appendix A.

MWP Process

The MWP Process for photonic integrated devices included:

- A review of existing materials;

- A review of related roles from O*NET[1], including core tasks and skills;
- A review of related educational programs identified using Lightcast[2];
- A framing of the needed technician skills and capabilities within the MOSAIC competency model; and
- 24 interviews and focus groups with experts and industry leaders.

A full list of existing materials reviewed, and references is in Appendix B.

An overview of the interview and focus group process is included in Appendix C.

Focus

Through our conversations with experts, we learned that photonic integrated devices are created to detect either a specific biological or specific chemical species, and that biological sensing is more advanced at this time than chemical sensing (Expert Interviews, 2024). Currently, chemical sensor devices are not manufactured at scale because the functionalized coating for these sensors is not as well developed. In contrast, more funding has been put toward medical testing, and therefore biological sensing is more well developed (Expert Interviews, 2024).

We also learned that it is not necessary to focus on manufacturing workforce needs for a specific type of sensor device. That is, photonic integrated devices will vary in their materials and structure depending on which biological or chemical species they are designed to detect. However, these variations will not generally be critical in their implications on the required tasks, skills, and competencies for technicians (Expert Interviews, 2024). While these variations are critical when considering what it takes as a creator (e.g., advanced degree training) to design the sensor device, once a blueprint for the sensor is designed, a technician can put together many different types of sensor devices from different blueprints without requiring vastly different skills and competencies (Expert Interviews, 2024). Technicians are not expected to know the chemical or biological background behind why the sensor device was designed as it was. Therefore, we do not need to focus on sensor devices for a particular chemical species, or for a particular biological species, or only using particular materials (Expert Interviews, 2024). As a result, we were able to focus our study on photonic integrated devices as a class, rather than needing to focus on one specific type of photonic integrated sensor device.

[1] O*NET is a publicly available database developed by the U.S. Department of Labor that provides job analysis results for a variety of occupations.
[2] Lightcast aggregates millions of publicly available job postings and career profiles daily to provide insights into the current labor market.

For the purposes of the current project, we therefore focused our efforts on photonic integrated devices. Generally, our findings are most relevant to bio-photonic integrated devices. However, we expect that much of what we learned about bio-photonic integrated devices will also pertain to photonic integrated devices designed to detect chemicals.

Parallel Products and Contributing Technologies

At the beginning of the MWP, the team identified product classes currently manufactured at scale that rely upon technologies that are most similar to those required to manufacture photonic integrated devices. The parallel product classes we identified were:

- Telecommunications photonics
- Microelectronics
- Medical sensors for diagnostics

These were identified as parallel products, as each bears some similarity to photonic integrated devices. Experts shared with us, universally, that the closest related field to photonic sensing is the field of telecommunications photonics (Expert Interviews, 2024). These experts said that in general, technicians manufacturing photonics integrated devices are generally expected to do similar tasks to and need similar competencies as technicians manufacturing telecommunications photonics devices (Expert Interviews, 2024). That is, all the same tools are anticipated to be used in the creation of photonic integrated devices as are used in the creation of telecommunications photonics devices. However, a key difference between telecommunications photonics and photonic integrated devices is that telecommunications devices employ fully sealed fiber optics. Photonic integrated devices are, in contrast, designed specifically to interact with the environment.

Microelectronics (including semiconductor manufacturing, which was mentioned frequently in interviews), like photonic integrated devices, requires that parts must be manufactured and assembled to a high degree of precision under controlled conditions (such as in clean rooms). Another key difference between photonic integrated devices and both telecommunications and microelectronics is that electrons are more orderly than photons (Expert Interviews, 2024). That is, electrons will tolerate slightly more misalignment between parts and continue to follow their intended paths. In contrast, photons escape through even small gaps between parts. As a result, manufacturing photonic integrated devices requires an exceptionally high degree of precision, even more so than these parallel products (Expert Interviews, 2024). Finally, understanding the manufacturing of medical sensors provides some insights into what will be required in manufacturing photonic integrated devices because both types of sensors must be treated with chemicals to enable them to detect specific biological or chemical elements (Expert Interviews, 2024).

Experts note that photonic integrated device manufacturing builds on a variety of disciplines. Contributing technologies and disciplines include photonics, mechanics, software, fluidics, and biochemistry (Expert Interviews, 2024). Importantly, experts note that there are very few programs at any level that teach at the nexus of these areas of expertise (Expert Interviews, 2024). Accordingly, very few people working with photonic integrated devices enter the field with interdisciplinary knowledge. Instead, interdisciplinary teams are often assembled at this point in the MRL/TRL lifecycle of experts with backgrounds in different disciplines (Expert Interviews, 2024).

Market Insights

The current readiness level for photonic integrated device development and manufacturing ranges from around MRL/TRL level 4 to level 6, depending on the specific application. A summary of key market observations derived from our interviews with subject matter experts and with leadership follows.

Cost: Currently photonic integrated devices are costly to produce. The majority of the cost is often in packaging, due to the extreme precision required to produce a unit (Expert Interviews, 2024). Some experts estimate that packaging is up to 80% of the cost of creating a photonic integrated device (Expert Interviews, 2024). Other experts noted that the average device is around $1,000 each, making experimentation in developing products difficult and expensive (Expert Interviews, 2024). Some noted that the cost of the actual optical chip is the most expensive part of the process, and that this cost is out of their direct control (Expert Interviews, 2024).

The equipment needed to achieve cost-reducing scale economies by increasing speed and volume is very expensive, so many companies have not invested in this equipment at this time. One expert noted that one method for reducing cost would be to relax constraints and specifications (Expert Interviews, 2024). If, for example, working sensors could be produced even with reduced component part alignment, the cost of manufacturing one finished product will decrease.

Another barrier to bringing down the cost of manufacturing photonic integrated devices is that most companies producing these devices do not create all components in house, and do not complete all steps of the process in house. Outsourcing the creation of components and parts of this process increases the cost of manufacturing devices (Expert Interviews, 2024).

Finally, most facilities are conducting time-consuming parts of the production process on individual devices rather than on wafers (Expert Interviews, 2024). For example, technicians generally conduct surface functionalization after the individual units have been created, rather than being able to conduct surface functionalization prior to dicing (Expert Interviews, 2024). This process flow is a result of how difficult it is for a technician to consistently functionalize a larger as opposed to smaller surface area. This increases the time that it takes to produce a single device. Some organizations are exploring how to move all production in-house or produce photonic integrated devices at the wafer level, but there are hurdles to both steps (Expert Interviews, 2024). Experts note that it will take time for a manufactured photonic integrated sensor to reach a price that would lead to wider market adoption (Expert Interviews, 2024).

Size: Like microelectronic products, photonic integrated devices (and associated circuit features) are very small and require extreme precision to produce. In addition, photonic integrated devices require a great deal of precision to manufacture and assemble at even the nano level to ensure photons follow the intended and necessary route (Expert Interviews, 2024). For example, exceptional precision is required for components including the waveguide and interconnecting optical components.

Vertical Integration: Vertical integration varies from company to company. Generally, however, most photonic integrated device producers do not do surface functionalization in house (Expert Interviews, 2024). Some do both fabrication and packaging, whereas others only fabricate, and others only create designs. All companies obtain the initial materials (chips/wafers) from foundries and anticipate continuing to do so (Expert Interviews, 2024).

The lack of vertical integration in producing photonic integrated devices can slow production significantly, with unintegrated workflows taking up to 6 months to create a sensor (Expert Interviews, 2024). The lack of integration stems in part from a low demand for a particular sensor each year as well as the complexity and specificity of skills currently needed to conduct each step of the production process. This combination of factors disincentivizes vertical integration at this stage of production, as it cannot be justified economically (Expert Interviews, 2024).

Some leaders anticipate moving toward vertical integration in the future, whereas others intend to keep the production of their photonic integrated devices unintegrated. One expert hypothesized a future in which two different companies set up factories side by side, with a literal hole cut in the wall to facilitate the flow of the materials from one company to completion at the other company (Expert Interviews, 2024). This expert noted that this practice is currently followed for some bottling companies. Experts noted that the cost and time it takes to set up a manufacturing line may also pose a barrier to product integration (Expert Interviews, 2024).

Overall, the cost of developing the product and lack of vertical integration in creating photonic integrated devices make these devices as they exist today difficult to scale in production.

Demand for the product: One leader described photonic integrated devices as "a solution in search of a problem." The market demand is still developing for these sensors, and currently, the demand is not extremely high.

Variation in the product: Photonic integrated devices vary tremendously. Each photonic integrated device must be designed specifically to detect a particular biological species or element, which requires different materials and design (Expert Interviews, 2024). Additionally, designs vary based on packaging and intended end use (Expert Interviews, 2024). The level of variability in the product may create challenges for scaling. If a company is relying on individual people to create the product without reliance on machinery, those individuals will need to be trained on each design. If machinery is being used, the machinery must be programmed for each successive design.

Automation: Currently, photonic integrated devices are created largely using a highly skilled, highly educated workforce that manually assembles each sensor from subcomponents (Expert Interviews, 2024). This is due in large part to the cost of the machinery required to automate the process in comparison to the current demand for the product (Expert Interviews, 2024). Specifically, the machinery needed to automate the process is prohibitively expensive at this point and companies are unlikely to yield the needed return on investment at this point to warrant the purchase of those machines. However, some companies are considering investing in such equipment in the next several years (Expert Interviews, 2024).

Unit of development: Currently, most facilities are executing time-consuming parts of the production process on individual devices, rather than completing them prior to dicing the wafer (e.g., surface functionalization). This kind of production requires a high degree of specificity and makes the process more time consuming. Completing these parts of production at the wafer level would reduce the amount of time needed to create each product (Expert Interviews, 2024). However, the exactness required to complete these parts of the production process makes it difficult to produce at the wafer rather than the device level (Expert Interviews, 2024). Most organizations currently intend to continue producing at the device level, although some are considering producing at the wafer level (Expert Interviews, 2024).

Time required: As discussed, currently photonic integrated devices take some time to produce in part due to the lack of vertical integration in the production process. Sensors may take up to 6 months to produce (Expert Interviews, 2024). This creates some challenges as sensors may have a shelf life (Expert Interviews, 2024).

Volume: Currently, photonic integrated devices are produced at a very low volume (Expert Interviews, 2024). In part this is because many companies working on photonic integrated devices are still functioning in earlier levels of the MRL/TRL framework. For other facilities, even completed prototypes have not moved to full scale production in part because of how manual the process for creating the sensors remains (Expert Interviews, 2024). Additionally, as noted before, the market for photonic integrated devices is still evolving. As a result, the demand for this product is not yet high enough to prompt high levels of manufacturing production (Expert Interviews, 2024). Experts note that even at scale, photonics manufacturing is likely to occur at a much lower rate than electronics manufacturing (for example, photonics sensors may be produced at 300/month vs 11,000/ week for electronics; Expert Interviews, 2024).

Profitability: Currently, the cost of developing photonic integrated devices is very high. Experts did not share their expectations around the price at which they would be able to sell photonic integrated devices. However, it is possible that the value-add of the photonic device does not exceed the cost in a number of potential applications.

Base Job Roles

First, experts shared that the label of "middle skilled technician" may be unclear. That is, to some, "middle skilled technician" may mean someone with less than a bachelor's degree; to others, it may include people with Master's degrees or PhDs. Notably, the definition of middle skilled technician may vary depending on the MRL and TRL of the technology; technicians working on the emerging technology at early MRL/TRL levels are likely to require more and more specialized expertise than those working on the emerging technologies once they reach full production.

For the purposes of this MWP, we projected job roles for middle skilled technicians working in higher volume manufacturing environments. As a result, our definition of "middle skilled technician" and corresponding role construction focused on people with less than a bachelor's degree. Throughout this report, we note some of the places where education or experience may vary as a function of production methodology or quantity.

Interviews and a review of existing documentation suggest the need for two specializations for technicians. Specifically, the manufacture of photonic integrated devices will require both Photonic Integrated Circuit (PIC) Technicians and Functionalization Technicians. PIC technicians will construct the photonic integrated circuits. The work that they do will be closest to the work done by technicians manufacturing microelectronics (Expert Interviews, 2024). PIC technicians will need to operate machinery to fabricate, package, or otherwise produce the photonic integrated devices themselves. Depending on the company, volume of production, and available equipment, these technicians may also need to manually align or assemble photonic integrated sensors.

Creating bio-photonic integrated devices requires attaching biomolecules to surfaces - a bioactive coating is needed to make the sensor sensitive to the targeted organism, virus, microbe, or so on. Therefore, one type of technician will need to have knowledge related to and skills in working with the materials used in these coatings. Functionalization technicians would be responsible for surface functionalization of the photonic integrated devices, to include mixing and applying chemical solutions to the circuits. These technicians will work with dousing systems and will handle chemical substances (Expert Interviews, 2024). They will therefore need background and training specific to handling those substances. Additionally, functionalization technicians will need to work with samples and pipette small amounts of liquids (Expert Interviews, 2024).

All technicians will need to interpret the meaning of tests and quality control analyses in production to inform both an understanding of the quality of the product as well as an understanding of the state of the production process itself. Importantly, at the innovator and creator level, we heard from experts that in addition to designers and engineers, data scientists will play a crucial role in establishing working blueprints for manufacturing processes producing bio-photonic integrated devices (Expert Interviews, 2024). Specifically, typical methods of analyses leveraging typical analytical approaches will not suffice in assessing photonic devices (Expert Interviews, 2024). Therefore, creators and innovators will include experts in data science and machine learning who effectively apply their skills to this unusual and unique context.

Parallel Occupations and Job Roles

A review of O*NET job classifications by subject matter experts surfaced 10 relevant occupations and job roles. These 10 roles were determined to be the most similar to what would be required from technicians manufacturing photonic integrated devices based on their tasks and activities, required background, safety requirements and expectations, and low required educational qualifications.

The 10 roles are:

- Materials Engineers
- Microsystems Engineers
- Photonics Engineers
- Nanosystems Engineers

- Electrical and Electronic Engineering Technologists and Technicians
- Nanotechnology Engineering Technologists and Technicians
- Photonics Technicians
- Materials Scientists
- Biological Technicians
- Chemical Technicians

Note that the majority of these occupations focus on assembling and producing objects at small scales. Two are specific to handling biological and chemical materials, as manufacturing photonic integrated devices will require surface functionalization in addition to assembling the product.

Base List of Tasks

A job or role analysis typically involves identifying tasks, knowledge, skills, abilities, and other characteristics necessary to complete a job and essential on day one of that job. The process typically involves consulting incumbents on the tasks they complete, then consulting on the knowledge, skills, abilities, and other characteristics necessary to do those tasks well (Breaugh, 2017). It is also possible to use observation and archival data to conduct a job analysis (Arthur, Doverspike, Kinney, & O'Connell, 2017; Breaugh, 2017).

In this case, we did not have access to either incumbents or supervisors for several reasons. First, we were not engaged by any specific organization to assess their workforce. The leaders we spoke to did not provide access to anyone who might be in a role equivalent to a technician incumbent or supervisor, often indicating they are too busy and they want their employees to focus on the work itself (Expert Interviews, 2024). Second, we are conducting a role analysis for jobs that do not yet exist in the incarnation that we are envisioning them. Therefore, there are very few available people who would functionally serve as incumbents or supervisors. As such, we had to rely on other methods of role analysis, specifically combining insights from expert interviews with archival data.

We predominantly focused on tasks and skills in this role analysis. Knowledge requirements for technicians are typically low (Expert Interviews, 2024), and abilities are considered to be more stable. As our focus was on developing the emerging photonic integrated sensor technician workforce, we largely assessed skills, which are highly trainable and transferable from other occupations. However, we do note a few abilities that are essential for manufacturing photonic integrated devices throughout this document.

We reviewed O*NET job descriptions for the parallel and contributing job roles in order to develop a base list of necessary tasks for PIC Technicians and Functionalization Technicians. To create these task lists, we focused first on tasks that were shared among more, rather than fewer, of these occupations. These tasks formed the basis of the task list for each position.

Some of the shared tasks, however, aligned more with the types of work we learned that creators or innovators might do during the technology development process. We removed these tasks from the list.

After these first two steps of narrowing the set of tasks, we then turned to our SME focus group and interview data. Tasks that were frequently cited or described as central were added back into our narrowed set of tasks. Therefore, we added in tasks with less overlap across these occupations when those tasks aligned with the insights we derived through interviews and focus groups.

Finally, through interviews and focus groups, we learned that precision and safety would be paramount for technicians manufacturing photonic integrated devices. One expert emphasized in particular the unusual importance of “fingerspitzengefühl,” meaning “fingertips feeling,” which is often taken as flair or instinct (Expert Interviews, 2024). In essence, producing a photonic integrated device requires an exceptional level of detail orientation and steadiness of the hand to ensure near perfect alignment and consistency (Expert Interviews, 2024). When we finalized our list of tasks for these positions, we made sure that the tasks included sufficient reference to safety and to precision and detail. Later in this report, we detail the skills needed by technicians; we followed the same process described above to determine the essential skills for each technician role.

Table 1, below, provides a comparison of the two positions. A full list of the tasks across both positions is provided in the left column. Tasks specific to PIC Technicians are highlighted in blue, and tasks specific to Functionalization Technicians are highlighted in red. Tasks that are shared by both roles are highlighted in purple. Overall, a total of 27 different tasks are covered across these two occupations. PIC Technicians have 20 identified tasks and Functionalization Technicians have 24 identified tasks. Three are unique to PIC Technicians, seven are unique to Functionalization Technicians, and 17 are shared.

Table 01. Tasks by Occupation

Task
Adjust equipment to ensure adequate performance
Analyze biological or chemical substances or related data to improve operations
Analyze performance of systems or equipment
Assemble equipment or components
Clean tools, equipment, facilities, or work areas
Complete all required safety training and refreshers
Document technical designs, procedures, or activities
Ensure use of proper personal protective equipment (PPE) including but not limited to safety glasses or goggles and gloves
Follow established processes to ensure consistency in outcomes
Inspect or measure thin films of carbon nanotubes, polymers, or inorganic coatings, using a variety of techniques or analytical tools
Maintain electronic, computer, or other technical equipment
Maintain operational records
Measure physical characteristics of materials, products, or equipment

Task
Measure physical or chemical properties of materials or substances
Mix, pour, or use processing chemicals or gasses according to safety standards or established operating procedures.
Monitor laboratory work to ensure compliance with set standards
Monitor operations to ensure adequate performance
Operate industrial processing or production equipment
Operate laboratory or field equipment
Prepare industrial materials for processing or use
Prepare specimens or materials for surface functionalization
Regularly inspect and maintain equipment to ensure safe operation
Set up equipment
Specify, coordinate, or conduct quality control or quality assurance programs or procedures
Test characteristics of materials or products
Test performance of equipment or systems
Train others on operational or work procedures

Tasks that are required only of PIC Technician are:

- Analyze performance of systems or equipment
- Monitor operations to ensure adequate performance
- Operate industrial processing or production equipment

Tasks that are required only of Functionalization Technicians are:

- Analyze biological or chemical substances or related data to improve operations
- Inspect or measure thin films of carbon nanotubes, polymers, or inorganic coatings, using a variety of techniques or analytical tools
- Measure physical or chemical properties of materials or substances
- Mix, pour, or use processing chemicals or gasses according to safety standards or established operating procedures.
- Monitor laboratory work to ensure compliance with set standards
- Operate laboratory or field equipment
- Prepare specimens or materials for surface functionalization

Base List of Skills

As with developing task lists, we reviewed and integrated O*NET job descriptions for the parallel and contributing job roles with insights from our interviews with experts in order to develop a base list of necessary skills for PIC Technicians and Functionalization Technicians.

Additionally, as a critical note, some of the key attributes necessary for technician success are abilities and not skills. While skills are trainable, abilities tend to be relatively stable in adulthood. This distinction has significant implications for hiring into technician positions, as abilities must typically be present at day one, before being hired into the job. Critical abilities for both technician roles will include:

- **Selective Attention**: The ability to concentrate on a task over a period of time without being distracted (National Center for ONET Development, 2021).
- **Manual Dexterity**: The ability to quickly move your hand, your hand together with your arm, or your two hands to grasp, manipulate, or assemble objects (National Center for ONET Development, 2021).

- **Finger Dexterity**: The ability to make precisely coordinated movements of the fingers of one or both hands to grasp, manipulate, or assemble very small objects (National Center for ONET Development, 2021).

Table 2, below, provides a comparison of skills required for each of the two positions. A full list of the skills across both positions is provided. Skills necessary for PIC Technicians would be highlighted in blue, and skills necessary for Functionalization Technicians only are highlighted in red. Note that none of the skills are necessary for PIC Technicians but not Functionalization Technicians. Skills necessary for both roles are marked in purple. Overall, a total of 22 different skills are covered across these two occupations. PIC Technicians have 20 identified skills and Functionalization Technicians have 22 identified skills. No skills are unique to PIC technicians, 2 are unique to Functionalization Technicians, and 20 are shared.

Importantly, note that there is more divergence in the *tasks* for each position, and less divergence in the *skills.* This is appropriate for middle-skilled technicians - baseline skills are essential for many technician positions, but their application varies depending on the specific requirements of each technician position.

Table 02. Skills By Occupation

Skill
Active Learning
Active Listening
Attention to Detail
Communication
Coordination
Critical Thinking
Equipment Maintenance
Judgment and Decision Making
Material Handling
Operation and Control
Operations Monitoring
Problem Solving Skills
Quality Control Analysis
Reading Comprehension
Safety Compliance
Science
Situational Awareness
Social Perceptiveness
Systems Analysis
Systematicity
Technical Proficiency
Troubleshooting

Definitions for the 22 skills are included below, 21 of which are drawn from O*NET.

- **Active Listening**: Giving full attention to what other people are saying, taking time to understand the points being made, asking questions as appropriate, and not interrupting at inappropriate times (National Center for ONET Development, 2021).

- **Active Learning:** Understanding the implications of new information for both current and future problem-solving and decision-making (National Center for ONET Development, 2021)

- **Attention to Detail**: Being careful about detail and thorough in completing work tasks (National Center for ONET Development, 2021).

- **Communication**: Conveying information effectively through speaking or writing (National Center for ONET Development, 2021).

- **Coordination:** Adjusting actions in relation to others' actions (National Center for

ONET Development, 2021).

- **Critical Thinking**: Using logic and reasoning to identify the strengths and weaknesses of alternative solutions, conclusions, or approaches to problems (National Center for ONET Development, 2021).
- **Equipment Maintenance**: Performing routine maintenance on equipment and determining when and what kind of maintenance is needed (National Center for ONET Development, 2021).
- **Judgment and Decision Making**: Considering the relative costs and benefits of potential actions to choose the most appropriate one (National Center for ONET Development, 2021).
- **Material Handling**: Moving, handling, and positioning materials using hands, arms, or equipment (National Center for ONET Development, 2021).
- **Operation and Control:** Controlling operations of equipment or systems (National Center for ONET Development, 2021).
- **Operations Monitoring**: Watching gauges, dials, or other indicators to make sure a machine is working properly (National Center for ONET Development, 2021).
- **Problem Solving Skills**: Identifying complex problems and reviewing related information to develop and evaluate options and implement solutions (National Center for ONET Development, 2021).
- **Quality Control Analysis**: Conducting tests and inspections of products, services, or processes to evaluate quality or performance (National Center for ONET Development, 2021).
- **Reading Comprehension**: Understanding written sentences and paragraphs in work-related documents (National Center for ONET Development, 2021).
- **Safety Compliance**: Following established procedures and guidelines to ensure safety in the workplace (National Center for ONET Development, 2021).
- **Science**: Using scientific rules and methods to solve problems (National Center for ONET Development, 2021).
- **Situational Awareness**: Being aware of physical conditions and surroundings and recognizing potential threats and opportunities (National Center for ONET Development, 2021).

- **Social Perceptiveness**: Being aware of others' reactions and understanding why they react as they do (National Center for ONET Development, 2021).
- **Systems Analysis**: Determining how a system should work and how changes in conditions, operations, and the environment will affect outcomes (National Center for ONET Development, 2021).
- **Systematicity:** Working in a methodical and organized way. This skill involves planning, following set procedures, and making sure tasks are done efficiently and accurately, all while sticking to a system or a plan.
- **Technical Proficiency**: Competency in applying specialized knowledge or skills (National Center for ONET Development, 2021).
- **Troubleshooting**: Determining causes of operating errors and deciding what to do about it (National Center for ONET Development, 2021).

One step in a role analysis is to link skills to tasks (Robinson-Morral et al., 2018). Specifically, it is important to identify which skills are necessary to effectively complete each task. When conducting this "linkage," it is important to ensure that each identified critical skill is linked to at least one task. If a skill is identified as critical but not linked to a single task, it cannot be considered necessary, as it is not then actually related to what the technician will need to do on the job. Typically, many skills will be linked to each task.

When a role analysis is conducted with incumbents and supervisors, supervisors will often be asked to engage in the linking process. However, job analysts (such as the MWP team) also often conduct the linkage process, determining through their expert judgment which skills identified are necessary to complete which tasks. Job analysts judgments have been found to have higher inter-rater reliability than judgments made by either incumbents or supervisors (Robinson-Morral et al., 2018). The I/O Psychologists on the MWP team conducted the linking process for photonic integrated device technicians. Each of the three I/O Psychologists linked skills to tasks. Skills that were linked to tasks by at least two out of the three I/O Psychologists were retained in the linkage table presented below. We verified that each of the critical skills identified previously was linked to at least one task.

Table 3, below, provides an overview of the skills needed to complete each task effectively.

Table 03. Skill to Task Linkage

Task	Skill(s) Needed
Assemble equipment or components	Attention to detail Reading comprehension Safety compliance Situational awareness
Set up equipment	Attention to detail Coordination Problem solving skills Safety compliance Situational awareness Technical proficiency
Follow established processes to ensure consistency in outcomes	Active listening Attention to detail Operations monitoring Quality control analysis Reading comprehension Safety compliance Systematicity Troubleshooting
Prepare industrial materials for processing or use	Attention to detail Material handling Safety compliance Science

Task	Skill(s) Needed
	Systematicity
Operate industrial processing or production equipment	Attention to detail Coordination Operation and Control Safety compliance Situational awareness Technical proficiency
Operate laboratory or field equipment	Coordination Material handling Operation and Control Safety compliance Situational awareness Technical proficiency
Adjust equipment to ensure adequate performance	Critical thinking Judgment and decision making Operations monitoring Problem solving skills Quality control analysis Safety compliance Situational Awareness Systems analysis Technical Proficiency Troubleshooting

Task	Skill(s) Needed
Mix, pour, or use processing chemicals or gasses according to safety standards or established operating procedures.	Attention to detail Coordination Material handling Quality control analysis Reading comprehension Safety compliance Science Situational Awareness Systematicity
Test performance of equipment or systems	Equipment maintenance Operation and control Operations monitoring Quality control analysis Systems analysis Technical proficiency Troubleshooting
Test characteristics of materials or products	Material handling Operation and control Operations monitoring Quality control analysis Science Troubleshooting
Measure physical characteristics of materials, products, or equipment	Attention to detail

Task	Skill(s) Needed
	Material handling Operation and Control Quality control analysis Science Technical proficiency
Measure physical or chemical properties of materials or substances	Attention to detail Material handling Operation and Control Quality control analysis Science
Prepare specimens or materials for surface functionalization	Attention to detail Material handling Safety compliance Science Systematicity
Inspect or measure thin films of carbon nanotubes, polymers, or inorganic coatings, using a variety of techniques or analytical tools	Attention to detail Operation and Control Quality control analysis Science Systematicity Technical proficiency
Monitor operations to ensure adequate performance	Equipment maintenance Judgment and decision making

Task	Skill(s) Needed
	Operation and Control Operations monitoring Quality control analysis Safety compliance Systematicity
Monitor laboratory work to ensure compliance with set standards	Attention to detail Judgment and decision making Operation and Control Operations monitoring Quality control analysis Safety compliance Systematicity
Regularly inspect and maintain equipment to ensure safe operation	Critical thinking Equipment maintenance Judgment and decision making Operations monitoring Problem solving skills Quality control analysis Safety compliance Systems analysis Technical proficiency Troubleshooting
Analyze performance of systems or equipment	Equipment maintenance

Task	Skill(s) Needed
	Operation and Control Operations monitoring Quality control analysis Systems analysis Technical proficiency Troubleshooting
Analyze biological or chemical substances or related data to improve operations	Attention to detail Critical thinking Judgment and decision making Operations monitoring Problem solving skills Quality control analysis Safety compliance Science Troubleshooting
Document technical designs, procedures, or activities	Communication Operation and Control Operations monitoring Reading comprehension Technical proficiency
Maintain operational records	Communication Critical thinking Operations monitoring

Task	Skill(s) Needed
	Reading comprehension
Maintain electronic, computer, or other technical equipment	Critical thinking Operation and Control Problem solving skills Technical proficiency
Clean tools, equipment, facilities, or work areas	Attention to detail Coordination Equipment maintenance Safety compliance Systematicity
Specify, coordinate, or conduct quality control or quality assurance programs or procedures	Critical thinking Reading comprehension Operations monitoring Quality control analysis Social Perceptiveness Systematicity Troubleshooting
Train others on operational or work procedures	Active listening Communication Coordination Critical thinking Social Perceptiveness

Task	Skill(s) Needed
Ensure use of proper personal protective equipment (PPE) including but not limited to safety glasses or goggles and gloves	Active listening Judgment and decision making Reading comprehension Safety compliance Situational awareness Social Perceptiveness Systematicity
Complete all required safety training and refreshers	Active listening Active learning Communication Reading comprehension Safety compliance Social Perceptiveness

Each skill was linked to at least one task. The number of tasks each skill was linked to is indicated below:

- Active Learning - 1 task
- Active Listening - 4 tasks
- Attention to Detail - 13 tasks
- Communication - 4 tasks
- Coordination - 6 tasks
- Critical Thinking - 7 tasks
- Equipment Maintenance - 5 tasks
- Judgment and Decision Making - 6 tasks

- Material Handling - 7 tasks
- Operation and Control: 12 tasks
- Operations Monitoring - 12 tasks
- Problem Solving Skills - 5 tasks
- Quality Control Analysis - 14 tasks
- Reading Comprehension - 8 tasks
- Safety Compliance - 16 tasks
- Science - 8 tasks
- Situational Awareness - 7 tasks
- Social Perceptiveness - 4 tasks
- Systematicity - 10 tasks
- Systems Analysis - 4 tasks
- Technical Proficiency - 11 tasks
- Troubleshooting - 8 tasks

The skills linked to the most tasks include safety compliance (16), quality control analysis (14), and attention to detail (13). The skill linked to the fewest tasks is active learning (1).

Competencies

Competencies can be defined as clusters of knowledge, skills, abilities, and other characteristics (KSAOs) that are needed for success in a particular job (Campion et al., 2011). In other words, KSAOs are foundational components to competency models, and competency models are composed of KSAOs. Each individual competency may have knowledge, skills, and/or abilities, but each individual competency will not necessarily have all three. Notably, competency models are frequently constructed from the bottom up. That is, KSAOs identified through the role analysis process are combined into clusters which are then named to provide a competency framework. In this case, we were instead combining two unique sources of information: a) our skill list as identified from expert interviews and O*NET data, and b) competencies from the 2013 Office of Personnel Management (OPC) MOSAIC competency model. As a result, our process was not fully bottom up, but rather iteratively top-down and bottom-up to first create a competency model and then match the competency model (using language in MOSAIC's) to skills.

Based on focus group results, and the necessary skills and tasks, the team reviewed the MOSAIC competency model to determine critical competencies for each of the two technician positions. Each competency listed in MOSAIC was carefully considered for inclusion in the technician competency models.

Ultimately, 54 of the MOSAIC competencies were included in the competency model for the identified technician positions. Additionally, one competency was created by the MWP team specifically for the technician positions addressed in this MWP to supplement the 54 competencies drawn from the MOSAIC competency model. These 55 competencies are organized into 15 competency clusters, which are further organized into 5 core capabilities for photonics integrated device technicians using expert judgment. The capabilities are identical for both technician positions, although the way that competencies may manifest for Functionalization and PIC Technicians are expected to vary, especially in the application of technical skills.

Below, we present a visual representation of the nested competency model followed by definitions for each capability, competency cluster, and competency. Note that definitions for capabilities and competency clusters emerged from this project, whereas definitions for individual competencies are adopted directly from the MOSAIC model.

Note that within an organization, competency models are scaled to illustrate what demonstrating each competency looks like at a variety of levels. For example, the behaviors associated with being "intentional" at an entry-level are likely to look different from the behaviors associated with being intentional five years in the same position. In this instance, we were not able to develop a leveled competency model. Our competencies are instead presented in a general sense. This approach has an impact on how we think about leveraging these competencies during hiring as it may be determined that a particular competency is needed day one on the job, However, a reasonably low level of that competency may in fact be needed for success, with the technician developing further in that competency on entry to the job.

Table 04. Competency Model - Photonics Integrated Device Technicians

Steady	Precise	Intentional	Technically Skilled	Collaborative
Internal Equilibrium ● Resilience ● Stress Tolerance	Perception ● Depth Perception ● Peripheral Vision ● Mental Visualization ● Perceptual Speed ● Spatial Orientation	Process Management ● Process Adherence+ ● Process Control ● Technical Documentation	Equipment ● Manufacturing ● Production and Processing ● Industrial Equipment Operation ● Mechanical	Collegiality ● Interpersonal Skills ● Leveraging Diversity ● Team Building ● Conflict Management ● Influencing/ Negotiating
Physical Skills ● Agility ● Hand-Eye Coordination ● Flexibility ● Stamina	Quality Control ● Incident Management ● Quality Assurance ● Quality Management	Compliance ● Hazardous Materials ● Standards ● Organizational Awareness	Technology ● Applies Technology to Tasks ● Computer Skills ● Technology Application	Communication ● Manages and Organizes Information ● Listening ● Reading ● Oral Communication ● Writing
Dependability ● Integrity/ Honesty ● Accountability ● Self Management	Detail Focus ● Attention to Detail ● Conscientiousness	Judgment and Decision Making ● Problem Solving ● Product Evaluation ● Technical Problem Solving ● Planning and Evaluation ● Decision Making	Technical Expertise ● Biology ● Chemistry ● Technical Competence	Development ● Learning ● Continual Learning ● Memory ● Teaches Others ● Develops Others

Steady

The first core capability is being *steady.* Technicians need to foster an internal equilibrium as well as physical skills to ensure that they can approach the mental and physical stressors related to their work.

- **Internal Equilibrium**

  Internal Equilibrium refers to a technician's internal steadiness, or the extent to which they are able to maintain balance and calmness under pressure and when in high stress situations.

  - **Resilience -** Deals effectively with pressure; remains optimistic and persistent, even under adversity. Recovers quickly from setbacks. (United States Office of Personnel Management, 2013)
  - **Stress Tolerance -** Deals calmly and effectively with high stress situations (for example, tight deadlines, hostile individuals, emergency situations, dangerous situations). (United States Office of Personnel Management, 2013)

- **Physical Skills**

  Physical Skills refer to a technician's physical steadiness, including their ability to work for long periods of time, adjust to the demands of different situations and needs, and work steadily on highly detailed tasks that require exceptional accuracy.

  - **Agility -** Bends, stretches, twists, or reaches out with the body, arms, or legs. (United States Office of Personnel Management, 2013)
  - **Eye-Hand Coordination -** Accurately coordinates one's eyes with one's fingers, wrists, or arms to perform job-related tasks (for example, to move, carry, or manipulate objects). (United States Office of Personnel Management, 2013)
  - **Flexibility -** Is open to change and new information; adapts behavior or work methods in response to new information, changing conditions, or unexpected obstacles; effectively deals with ambiguity. (United States Office of Personnel Management, 2013)
  - **Stamina -** Exerts oneself physically over long periods of time without tiring (which may include performing repetitive tasks such as data entry or coding). (United States Office of Personnel Management, 2013)

- **Dependability**
    - **Integrity/Honesty -** Contributes to maintaining the integrity of the organization; displays high standards of ethical conduct and understands the impact of violating these standards on an organization, self, and others; is trustworthy. (United States Office of Personnel Management, 2013)
    - **Accountability -** Holds self and others accountable for measurable high-quality, timely, and cost-effective results. Determines objectives, sets priorities, and delegates work. Accepts responsibility for mistakes. Complies with established control systems and rules. (United States Office of Personnel Management, 2013)
    - **Self-Management -** Sets well-defined and realistic personal goals; displays a high level of initiative, effort, and commitment towards completing assignments in a timely manner; works with minimal supervision; is motivated to achieve; demonstrates responsible behavior. (United States Office of Personnel Management, 2013)

Precise

The second core capability is being *precise.* Technicians require visual perception, a keen focus on quality control, and a focus on details in order to manage the demands of assembling technology that requires alignment and accuracy on a nano level.

- **Perception**

  Perception refers to a technician's visual acuity and awareness, including depth perception and peripheral vision, the ability to visualize things mentally, speed of perception, and spatial orientation.

    - **Depth Perception -** Accurately judges which of several objects is closer or farther away from the observer, or the distance between an object and the observer. (United States Office of Personnel Management, 2013)
    - **Peripheral Vision -** Sees objects or movement of objects to one's side when the eyes are focused forward. (United States Office of Personnel Management, 2013)
    - **Mental Visualization -** Sees things in the mind by mentally organizing and processing symbols, pictures, graphs, objects, or other information (for example, sees a building from a blueprint, or sees the flow of work

activities from reading a work plan). (United States Office of Personnel Management, 2013)

  - **Perceptual Speed** - Quickly and accurately sees detail in words, numbers, pictures, and graphs. (United States Office of Personnel Management, 2013)
  - **Spatial Orientation -** Knows one's location in relation to the environment; determines where other objects are in relation to one's self (for example, when using a map). (United States Office of Personnel Management, 2013)

- **Quality Control**

  Quality Control refers to a technician's knowledge of quality control mechanisms and ability to implement them, including evaluating resolving incidents, and managing and assuring quality workmanship.

  - **Incident Management -** Knowledge of the tactics, technologies, principles, and processes to protect, analyze, prioritize, and handle incidents. (United States Office of Personnel Management, 2013)
  - **Quality Assurance -** Knowledge of the principles, methods, and tools of quality assurance and quality control used to ensure a product fulfills functional requirements and standards. (United States Office of Personnel Management, 2013)
  - **Quality Management -** Knowledge of the principles, methods, and tools of quality assurance, quality control, and reliability used to ensure that a project, system, or product fulfills requirements and standards. (United States Office of Personnel Management, 2013)

Detail Focus

Technicians must be detail focused to ensure technology is manufactured to precision, including demonstrating a keen attention to detail and displaying conscientiousness in accurately completing work tasks.

  - **Attention to Detail -** Is thorough when performing work and conscientious about attending to detail. (United States Office of Personnel Management, 2013)
  - **Conscientiousness** - Displays a high level of effort and commitment towards performing work; demonstrates responsible behavior. (United States Office of Personnel Management, 2013)

Intentional

The third core capability is being *intentional.* Technicians must be deliberate, thoughtful, intentional, and consistent in their approach to work, including managing processes, compliance, and exercising excellent judgment and decision making.

- **Process Management**

  Process Management refers to a technician's knowledge of and ability to adhere to established processes, including demonstrating control over processes and maintaining technical documentation.

  - **Process Adherence[3] -** Capacity to adhere to established processes exactly and consistently.

  - **Process Control -** Knowledge of the principles, methods, and procedures used for the automated control of a process, including the design, development, and maintenance of associated software, hardware, and systems. (United States Office of Personnel Management, 2013)

  - **Technical Documentation -** Knowledge of procedures for developing technical and operational support documentation. (United States Office of Personnel Management, 2013)

- **Compliance**

  Compliance refers to a technician's focus on following procedures that protect both themselves and their organization, including safety procedures for working with hazardous materials, standards guiding their work, and organizational procedures and requirements.

  - **Hazardous Materials -** Knowledge of hazardous materials and waste and their uses, interactions, dangers, production, handling, storage, and disposal. (United States Office of Personnel Management, 2013)

  - **Standards -** Knowledge of standards that either are compliant with or derived from established standards or guidelines. (United States Office of Personnel Management, 2013)

  - **Organizational Awareness -** Knows the organization's mission and functions, and how its social, political, and technological systems work and

[3] Process adherence is the only competency not drawn directly from MOSAIC. Our interviews with experts continually reinforced the importance of following established processes. While several MOSAIC competencies somewhat address this concept, it was critical enough in our interview responses to warrant the creation of an additional competency

operates effectively within them; this includes the programs, policies, procedures, rules, and regulations of the organization. (United States Office of Personnel Management, 2013)

- **Judgment and Decision Making**

  Judgment and Decision Making refers to a technician's ability to process information, evaluate and troubleshoot challenges, and make decisions. This includes problem solving, evaluating, planning, and decision making.

  - **Problem Solving -** Identifies problems; determines accuracy and relevance of information; uses sound judgment to generate and evaluate alternatives, and to make recommendations. (United States Office of Personnel Management, 2013)

  - **Technical Problem Solving -** Troubleshoots, diagnoses, analyzes, and identifies system malfunctions to determine the source and cause of the problem. (United States Office of Personnel Management, 2013)

  - **Product Evaluation -** Knowledge of methods for researching and analyzing external products to determine their potential for meeting organizational standards and business needs. (United States Office of Personnel Management, 2013)

  - **Planning and Evaluating -** Organizes work, sets priorities, and determines resource requirements; determines short- or long-term goals and strategies to achieve them; coordinates with other organizations or parts of the organization to accomplish goals; monitors progress and evaluates outcomes. (United States Office of Personnel Management, 2013)

  - **Decision Making -** Makes sound, well-informed, and objective decisions; perceives the impact and implications of decisions; commits to action, even in uncertain situations, to accomplish organizational goals; causes change. (United States Office of Personnel Management, 2013)

Technically Skilled

The fourth core capability is being *technically skilled.* Technicians need to have knowledge and experience operating equipment, leveraging technology, and applying their specific technical expertise to manufacture photonic integrated devices.

- **Equipment**

  Equipment refers to a technician's ability to appropriately operate and maintain manufacturing and industrial equipment. This includes understanding the manufacturing process, operating equipment, and mechanical maintenance.

  - **Manufacturing -** Knowledge of the specifications, tools, inputs, raw materials, outputs, and waste related to the manufacture of prototypes, models, systems, or other products. (United States Office of Personnel Management, 2013)
  - **Production and Processing -** Knowledge of inputs, outputs, raw materials, waste, quality control, costs, maintaining inventory, and techniques for maximizing the manufacture and distribution of goods. (United States Office of Personnel Management, 2013)
  - **Industrial Equipment Operation -** Knowledge of principles and methods for operating industrial equipment. (United States Office of Personnel Management, 2013)
  - **Mechanical -** Knowledge of machines and tools, including their designs, uses, benefits, repair, and maintenance. (United States Office of Personnel Management, 2013)

- **Technology**

  Technology refers to a technician's application of technology, including computers, to complete their tasks. This includes applying technology and tools, using computer skills, and using technology to analyze and communicate information.

  - **Applies Technology to Tasks -** Selects and understands procedures, machines, or tools that will produce the desired results; identifies or solves problems in machines, computers, or other technologies as they are related to performing tasks. (United States Office of Personnel Management, 2013)
  - **Computer Skills -** Uses computers, software applications, databases, and automated systems to accomplish work. (United States Office of Personnel Management, 2013)
  - **Technology Application -** Uses machines, tools, instruments, or equipment effectively; uses computers and computer applications to

analyze and communicate information in the appropriate format. (United States Office of Personnel Management, 2013)

- **Technical Expertise**

  Technical Expertise refers to a technician's application of their specialized technical knowledge and expertise to their work. Depending on the focus of the technician's work, this may include knowledge of biology, chemistry, or other technical competence.

  - **Biology -** Knowledge of the environment, plant and animal living tissue, cells, organisms, and entities, including their functions, interdependencies and interactions with each other and the environment. (United States Office of Personnel Management, 2013)

  - **Chemistry -** Knowledge of the concepts, principles, and theories of the composition, structure, and properties of substances, and of the chemical processes and transformations, including uses of chemicals and their interactions, danger signs, production techniques, and disposal methods. (United States Office of Personnel Management, 2013)

  - **Technical Competence -** Uses knowledge that is acquired through formal training or extensive on-the-job experience to perform one's job; works with, understands, and evaluates technical information related to the job; advises others on technical issues. (United States Office of Personnel Management, 2013)

Collaborative

The final core capability is being *collaborative.* Technicians must be collegial with each other as well as strong communications. Technicians must also commit themselves not only to their own development, but to the development of others.

- **Collegiality**

  A technician's collegiality refers to their ability to develop and maintain effective relationships with others at work. This includes interpersonal skills, fostering inclusion, team building, conflict management, and the ability to influence others.

  - **Interpersonal Skills -** Shows understanding, friendliness, courtesy, tact, empathy, concern, and politeness to others; develops and maintains effective relationships with others; may include effectively dealing with individuals who are difficult, hostile, or distressed; relates well to people from varied backgrounds and different situations; is sensitive to cultural diversity, race, gender, disabilities, and other individual differences. (United States Office of Personnel Management, 2013)

- **Leveraging Diversity -** Fosters an inclusive workplace where diversity and individual differences are valued and leveraged to achieve the vision and mission of the organization. (United States Office of Personnel Management, 2013)
- **Team Building -** Inspires and fosters team commitment, spirit, pride, and trust. Facilitates cooperation and motivates team members to accomplish group goals. (United States Office of Personnel Management, 2013)
- **Conflict Management -** Manages and resolves conflicts, grievances, confrontations, or disagreements in a constructive manner to minimize negative personal impact. (United States Office of Personnel Management, 2013)
- **Influencing/Negotiating -** Persuades others to accept recommendations, cooperate, or change their behavior; works with others towards an agreement; negotiates to find mutually acceptable solutions. (United States Office of Personnel Management, 2013)

- **Communication**

  Technicians must also be skilled in communication, including managing and communicating information, listening, reading, and communicating effectively both verbally and in writing.

  - **Manages and Organizes Information -** Identifies a need; gathers, organizes, and maintains information; determines its importance and accuracy, and communicates it by a variety of methods. (United States Office of Personnel Management, 2013)
  - **Listening -** Receives, attends to, interprets, and responds to verbal messages and other cues such as body language in ways that are appropriate to listeners and situations. (United States Office of Personnel Management, 2013)
  - **Reading -** Understands and interprets written material, including technical material, rules, regulations, instructions, reports, charts, graphs, or tables; applies what is learned from written material to specific situations. (United States Office of Personnel Management, 2013)

- **Oral Communication -** Expresses information (for example, ideas or facts) to individuals or groups effectively, taking into account the audience and nature of the information (for example, technical, sensitive, controversial); makes clear and convincing oral presentations; listens to others, attends to nonverbal cues, and responds appropriately. (United States Office of Personnel Management, 2013)

- **Writing -** Recognizes or uses correct English grammar, punctuation, and spelling; communicates information (for example, facts, ideas, or messages) in a succinct and organized manner; produces written information, which may include technical material, that is appropriate for the intended audience. (United States Office of Personnel Management, 2013)

- **Development**

  A technician who is development oriented invests in their own learning and the development of others. This includes learning, continual learning, remembering information, teaching and developing others.

  - **Learning -** Uses efficient learning techniques to acquire and apply new knowledge and skills; uses training, feedback, or other opportunities for self-learning and development. (United States Office of Personnel Management, 2013)

  - **Continual Learning -** Assesses and recognizes own strengths and weaknesses; pursues self- development. (United States Office of Personnel Management, 2013)

  - **Memory -** Recalls information that has been presented previously. (United States Office of Personnel Management, 2013)

  - **Teaches Others -** Helps others learn; identifies training needs; provides constructive reinforcement; coaches others on how to perform tasks; acts as a mentor. (United States Office of Personnel Management, 2013)

  - **Developing Others -** Develops the ability of others to perform and contribute to the organization by providing ongoing feedback and by providing opportunities to learn through formal and informal methods. (United States Office of Personnel Management, 2013)

Next, the I/O psychologists conducted a linkage of competencies to tasks, matching the 15 competency clusters to tasks. As with the skills to task linkage, we used expert judgment to determine which competency or competencies would be needed to complete each task. Again, each competency needed to be linked to at least one task. Competencies were necessary for task completion if at least two out of the three I/O psychologists endorsed that linkage. Table 5, below, displays the results of this assessment.

Table 05. Competency to Task Linkage

Task	Competency/ies Needed
Assemble equipment or components	Communication Compliance Detail Focus Equipment Perception Physical Skills Technical Expertise
Set up equipment	Compliance Detail Focus Equipment Judgment and Decision Making Perception Physical Skills Technical Expertise
Follow established processes to ensure consistency in outcomes	Communication Compliance Dependability Detail Focus

Task	Competency/ies Needed
	Internal Equilibrium Judgment and Decision Making Process Management Quality Control
Prepare industrial materials for processing or use	Compliance Dependability Detail Focus Equipment Internal Equilibrium Physical Skills Process Management Technical Expertise
Operate industrial processing or production equipment	Compliance Detail Focus Equipment Internal Equilibrium Perception Physical Skills Process Management Technology Technical Expertise

Task	Competency/ies Needed
Operate laboratory or field equipment	Compliance Detail Focus Equipment Internal Equilibrium Perception Physical Skills Process Management Technology Technical Expertise
Adjust equipment to ensure adequate performance	Compliance Dependability Detail Focus Equipment Judgment and Decision Making Perception Physical Skills Process Management Quality Control Technical Expertise
Mix, pour, or use processing chemicals or gasses according to safety standards or established operating procedures.	Communication Compliance Dependability

Task	Competency/ies Needed
	Detail Focus Internal Equilibrium Judgment and Decision Making Perception Physical Skills Process Management Quality Control Technical Expertise
Test performance of equipment or systems	Dependability Detail Focus Equipment Judgment and Decision Making Physical Skills Process Management Quality Control Technical Expertise Technology
Test characteristics of materials or products	Dependability Detail Focus Judgment and Decision Making Physical Skills Process Management

Task	Competency/ies Needed
	Quality Control Technical Expertise Technology
Measure physical characteristics of materials, products, or equipment	Detail Focus Equipment Physical Skills Quality Control Technical Expertise Technology
Measure physical or chemical properties of materials or substances	Detail Focus Physical Skills Quality Control Technical Expertise Technology
Prepare specimens or materials for surface functionalization	Compliance Detail Focus Internal Equilibrium Physical Skills Process Management Technical Expertise
Inspect or measure thin films of carbon nanotubes, polymers, or inorganic	Communication

Task	Competency/ies Needed
coatings, using a variety of techniques or analytical tools	Detail Focus Internal Equilibrium Judgment and Decision Making Physical Skills Process Management Quality Control Technical Expertise Technology
Monitor operations to ensure adequate performance	Compliance Dependability Detail Focus Equipment Judgment and Decision Making Process Management Quality Control Technology
Monitor laboratory work to ensure compliance with set standards	Compliance Dependability Detail Focus Judgment and Decision Making Process Management Quality Control

Task	Competency/ies Needed
	Technology
Regularly inspect and maintain equipment to ensure safe operation	Compliance Dependability Detail Focus Equipment Judgment and Decision Making Physical Skills Process Management Quality Control Technical Expertise
Analyze performance of systems or equipment	Compliance Dependability Detail Focus Equipment Judgment and Decision Making Process Management Quality Control Technical Expertise Technology
Analyze biological or chemical substances or related data to improve operations	Compliance Dependability

Task	Competency/ies Needed
	Detail Focus Internal Equilibrium Judgment and Decision Making Quality Control Process Management Technical Expertise
Document technical designs, procedures, or activities	Communication Compliance Dependability Detail Focus Physical Skills Process Management Technical Expertise Technology
Maintain operational records	Communication Compliance Dependability Detail Focus Judgment and Decision Making Process Management
Maintain electronic, computer, or other technical equipment	Compliance

Task	Competency/ies Needed
	Dependability Detail Focus Judgment and Decision Making Physical Skills Process Management Technology Technical Expertise
Clean tools, equipment, facilities, or work areas	Compliance Dependability Detail Focus Equipment Physical Skills Process Management
Specify, coordinate, or conduct quality control or quality assurance programs or procedures	Collegiality Communication Compliance Dependability Detail Focus Development Internal Equilibrium Judgment and Decision Making Process Management

Task	Competency/ies Needed
	Quality Control
Train others on operational or work procedures	Collegiality Communication Compliance Dependability Development Equipment Internal Equilibrium Judgment and Decision Making Physical Skills Process Management Technical Expertise
Ensure use of proper personal protective equipment (PPE) including but not limited to safety glasses or goggles and gloves	Collegiality Communication Compliance Dependability Development Internal Equilibrium Judgment and Decision Making Perception Physical Skills Process Management

Task	Competency/ies Needed
	Quality Control
Complete all required safety training and refreshers	Collegiality Communication Compliance Dependability Development Quality Control

Each competency cluster was linked to at least one task. The number of tasks each competency cluster was linked to is listed below:

- Collegiality - 4 tasks
- Communication - 10 tasks
- Compliance - 23 tasks
- Dependability - 19 tasks
- Detail Focus - 24 tasks
- Development - 4 tasks
- Equipment - 13 tasks
- Internal Equilibrium - 11 tasks
- Judgment and Decision Making - 17 tasks
- Perception - 7 tasks
- Physical Skills - 19 tasks
- Process Management - 22 tasks
- Quality Control - 16 tasks

- Technical Expertise - 19 tasks
- Technology - 12 tasks

The competencies linked to the most tasks are detail focus (23), compliance (23), process management (22), dependability (19), physical skills (19), technical expertise (19), judgment and decision making (17), and quality control (16). Collegiality and development are linked to the fewest tasks, at 4 each.

As noted previously, competencies are clusters of skills, knowledge, abilities, and behaviors that differentiate between high and low performers. Competencies may, but do not always, include and involve skills. Typically, a competency model is created using a bottom-up process whereby knowledge, skills, abilities, and other characteristics are clustered and named. In this case, we are integrating two sources of information: a) skills as identified through O*NET and interviews, and b) MOSAIC competencies, clustered and named. Therefore, matching skills to competencies in this case did not follow a purely bottom-up process. Instead, the I/O psychologists reviewed definitions from these two different sources of information to sort skill identified through O*NET into the competencies built on MOSAIC.

The results of this process are presented below. We note in the table below which competency cluster each skill most clearly aligns with. Note that each skill is associated with only one competency cluster, and not all competency clusters are represented by skills. In other words, some of the identified competency clusters are more skill-based and others more knowledge and ability-based. We included the three abilities (selective attention, manual dexterity, and finger dexterity), denoted in bold, in this linkage. Finally, we noted a personality trait, conscientiousness, that will also be essential for dependability. It is underlined in the table below.

Table 06. Skill to Competency Linkage

Competency	**Skill**
Internal Equilibrium	**Selective Attention**
Physical Skills	Coordination **Finger Dexterity** **Manual Dexterity** Material Handling
Dependability	<u>Conscientiousness</u>

Competency	**Skill**
Perception	Situational Awareness
Quality Control	Quality Control Analysis
Detail Focus	Attention to Detail
Process Management	Systematicity Operations Monitoring
Compliance	Safety Compliance
Judgment and Decision Making	Critical Thinking Judgment and Decision Making Problem Solving Skills Systems Analysis Troubleshooting
Equipment	Equipment Maintenance
Technology	Operation and Control
Technical Expertise	Science Technical Proficiency
Collegiality	Social Perceptiveness
Communication	Reading Comprehension Communication Active Listening
Development	Active Learning

Needed at Entry

Next, leveraging insights from our interviews, we sought to determine which tasks, skills, and competencies might be needed at entry. Due to the differences in requirements for technicians who are producing photonic integrated devices using more manual, versus more automated, processes, we created needed at entry lists for technician positions (who will work with more machines and equipment on automated processes), and tentative needed at entry lists for technologist positions (who will work with more manual processes).

Tasks that a technician or technologist would need to perform on the very first day are noted in Table 7.

Table 07. Tasks Needed at Entry

Task	PIC Technician	PIC Technologist	Functionalization Technician	Functionalization Technologist
Assemble equipment or components		X		X
Set up equipment		X		X
Prepare industrial materials for processing or use				
Operate industrial processing or production equipment		X		
Operate laboratory or field equipment				X
Adjust equipment to ensure adequate performance		X		X
Mix, pour, or use processing chemicals or gasses according to safety standards or established operating procedures.				
Test performance of equipment or systems		X		X
Test characteristics of materials or products		X		X
Follow established processes to ensure consistency in outcomes	X	X	X	X
Measure physical characteristics of materials, products, or equipment				
Measure physical or chemical properties of materials or substances				X

Task	PIC Technician	PIC Technologist	Functionalization Technician	Functionalization Technologist
Prepare specimens or materials for surface functionalization				
Inspect or measure thin films of carbon nanotubes, polymers, or inorganic coatings, using a variety of techniques or analytical tools				
Monitor operations to ensure adequate performance				
Monitor laboratory work to ensure compliance with set standards				
Regularly inspect and maintain equipment to ensure safe operation				
Analyze performance of systems or equipment				
Analyze biological or chemical substances or related data to improve operations				
Document technical designs, procedures, or activities				
Maintain operational records	X	X	X	X
Maintain electronic, computer, or other technical equipment		X		X
Clean tools, equipment, facilities, or work areas	X	X	X	X
Specify, coordinate, or conduct quality control or				

Task	PIC Technician	PIC Technologist	Functionalization Technician	Functionalization Technologist
quality assurance programs or procedures				
Train others on operational or work procedures				
Ensure use of proper personal protective equipment (PPE) including but not limited to safety glasses or goggles and gloves	X	X	X	X
Complete all required safety training and refreshers	X	X	X	X

Note that very few tasks are needed on the first day. Technicians and technologists should be ready to complete all required safety training and should be able to follow established processes. They should be prepared to keep their work area clean. Technologists should also have some experience in the basic expertise required for their area, whether that is setting up and running equipment of some kind or handling materials. Technologists should also have more safety training coming into the job. Almost everything else will be trained on the job.

Skills that a technician or technologist would need to demonstrate on the very first day are noted in Table 8.

Table 08. Skills Needed at Entry

Skill	PIC Technician	PIC Technologist	Functionalization Technician	Functionalization Technologist
Active Learning	X	X	X	X
Active Listening	X	X	X	X
Attention to Detail	X	X	X	X
Communication	X	X	X	X

Skill	**PIC Technician**	**PIC Technologist**	**Functionalization Technician**	**Functionalization Technologist**
Coordination	X	X	X	X
Critical Thinking	X	X	X	X
Equipment maintenance		X		X
Judgment and Decision Making	X	X	X	X
Material Handling				X
Operation and Control		X		X
Operations Monitoring				
Problem Solving Skills		X		X
Quality Control Analysis				
Reading Comprehension	X	X	X	X
Safety Compliance		X		X
Science				X
Situational Awareness	X	X	X	X
Social Perceptiveness	X	X	X	X
Systems Analysis				

Skill	PIC Technician	PIC Technologist	Functionalization Technician	Functionalization Technologist
Systematicity	X	X	X	X
Technical Proficiency		X		X
Troubleshooting	X	X	X	X

Technicians and technologists must come in with skills related to learning and growing their skillset, since so much must be learned on the job. Due to the nature of the work of producing photonic integrated sensors, technicians and technologists must both come in with skills related to details, quality control, and critical thinking. Technical proficiency and more equipment-specific skills can and should be learned on the job. Technologists should also have some level of experience in equipment maintenance. Functionalization technologists should further have some experience in science and material handling. However, the specifics of equipment maintenance, science, and material handling for that particular role and organization should be taught on the job. Finally, all three abilities - selective attention, manual dexterity, and finger dexterity - as well as conscientiousness are needed at entry.

Competencies that a technician or technologist would need to demonstrate on the very first day are noted in Table 9.

Table 09. Competencies Needed at Entry

Competency	PIC Technician	PIC Technologist	Functionalization Technician	Functionalization Technologist
Collegiality	X	X	X	X
Communication	X	X	X	X
Compliance		X		X
Dependability	X	X	X	X
Detail Focus	X	X	X	X

Competency	PIC Technician	PIC Technologist	Functionalization Technician	Functionalization Technologist
Development	X	X	X	X
Equipment		X		X
Internal Equilibrium	X	X	X	X
Judgment and Decision Making	X	X	X	X
Perception	X	X	X	X
Physical Skills	X	X	X	X
Process Management	X	X	X	X
Quality Control		X		X
Technology		X		X
Technological Expertise		X		X

Note that technologists should have basic competency in nearly the entire competency framework on entry. As discussed previously, meeting basic competence on entry does not require expert-level competence in each of these areas. Entry-level competence required will necessarily be at a lower, or more basic level than what would be expected of a seasoned technician or technologist. Technicians are expected to learn about one third of these competencies on the job.

Lists of tasks, skills, and competencies needed at entry for technicians are provided below. Note that while the tasks needed at entry differ slightly between PIC and Functionalization Technicians, the skills and competencies do not. Each skill and competency needed at entry is matched to at least one of the tasks that is needed at entry.

PIC Technician tasks needed at entry, in full:

- Follow established processes to ensure consistency in outcomes
- Maintain operational records
- Clean tools, equipment, facilities, or work areas
- Ensure use of proper personal protective equipment (PPE) including but not limited to safety glasses or goggles and gloves
- Complete all required safety training and refreshers

Functionalization Technician tasks needed at entry, in full:

- Follow established processes to ensure consistency in outcomes
- Maintain operational records
- Clean tools, equipment, facilities, or work areas
- Ensure use of proper personal protective equipment (PPE) including but not limited to safety glasses or goggles and gloves
- Complete all required safety training and refreshers

Technician skills needed at entry, in full:

- Active Learning
- Active Listening
- Attention to Detail
- Communication
- Coordination
- Critical Thinking
- Judgment and Decision Making
- Problem Solving Skills
- Reading Comprehension
- Situational Awareness
- Social Perceptiveness
- Systematicity

- Troubleshooting

Technician competencies needed at entry, in full:

- Collegiality
- Communication
- Dependability
- Detail Focus
- Development
- Internal Equilibrium
- Judgment and Decision Making
- Perception
- Physical Skills
- Process Management

Our findings align with and build on existing research related to the skills and tasks required of manufacturing workforces. First, our findings align with the “soft” skills needed for success in a career in optics or photonics according to the International Society for Photonics and Optics (SPIE; Resnick, 2023). As one example, Resnick highlights communication, problem solving, and collaboration (collegiality) as three of the top eight essential skills (2023) for a career in photonics.

Second, Moore, Field, and Kirchain (2024) note that there is a significant gap between workers’ skills and what companies need in their manufacturing workforce. Moore et al. (2024) identified key skills across different jobs, including for Chemical and Photonics Technicians. While the goal of their work was to identify critical skills needed across occupations to enable the more efficient allocation of training resources, the specific skills they identified also resonate with the tasks and skills we identified through the current project. Specifically, Moore et al. (2024) note the importance of preparing specimens, tools, or equipment; repairing and maintaining equipment; monitoring processes; evaluating for quality; making decisions; and controlling machines and processes generally - all components that also emerged during our work analysis. For Chemical and Photonics Technicians specifically, Moore et al. (2024) underscored skills in general physical activities and handling and moving objects, which likewise featured heavily in our role analysis.

Finally, Moore et al. (2023) forecasted several similar work activities as critical for technicians creating photonic integrated devices, including fabricating and testing devices; performing analyses setting up and operating test apparatuses, assembly, or processing equipment; assembling optical components; maintaining working environments to clean room standards; and mixing, pouring, or using chemicals. They also identified similar skills as essential to performing these tasks as those identified in the current MWP, including thinking critically; analyzing data; troubleshooting; estimating and judging characteristics; preparing specimens, tools, and equipment; and repairing and maintaining equipment. Like us, they emphasized precision and safety. Moore et al. (2023) note that the photonics industry will need a technician workforce capable of critical thinking and creative responding. We note that this will be particularly critical for the technologist, whose work will be more manual than the technician. Specifically, the technologist workforce will likely serve as a key part of transitioning from prototyping to full-scale, equipment-driven manufacturing. Since the technologist will be conducting more of their work manually, it is particularly important they are strong in critical and creative thinking.

Equipment and Work Context

The work context for manufacturing photonic integrated devices is unique as compared to its PC technologies for a variety of reasons. First, manufacturing photonic integrated devices requires working with microfluidics for analytic delivery (Expert Interviews, 2024). Second, there are expected differences in design, testing, and packaging for manufacturing disposable and reusable photonic integrated devices depending on what is being detected and in what final product (Expert Interviews, 2024). This may lead to differences in the equipment used and process followed.

Finally, one theme that emerged repeatedly in our interviews is that the level of alignment required to manufacture photonic integrated devices is so high that it is often done by hand (Expert Interviews, 2024). This means that field calibration is often a manual process. The machines that might be used to calibrate and align parts are extremely expensive, and without a robust market for particular types of sensors, the cost of those machines may outweigh their usefulness (Expert Interviews, 2024). In short, the unique work context for manufacturing photonic devices means that the equipment used to manufacture these devices may vary from facility to facility. Equipment will depend on a number of factors, including:

- Which components of the process are done in-house, of fabrication, packaging, dicing, and functionalization
- The type and variety of photonic integrated devices manufactured in the facility (including what is being detected)

- The end product and use environment (e.g., hot or cold environments) for the photonic integrated devices
- The size of the market and demand for those particular devices

Some of the equipment that might be leveraged in manufacturing photonic devices include:

1. **Photolithography Equipment.** Photolithography Equipment creates patterns on a substrate. In the case of photonic integrated devices, this will typically be a silicon wafer. It is used in micro- and nanofabrication processes.
2. **Deposition Equipment.** Deposition Equipment applies a metal coating (such as metals, oxides, polymers) to the sensor's surface. It is used during fabrication.
3. **Etching Equipment.** Etching Equipment is used on the silicon wafer to modulate the refractive index. It is used during fabrication.
4. **Dicing and Wafer Bonding Equipment.** Dicing and Wafer Bonding Equipment is used to dice silicon wafers into individual devices. This is sometimes done before and sometimes after surface functionalization.
5. **Packaging and Assembly Equipment.** Packaging and Assembly Equipment is used to package the photonic integrated devices. It is often done at the device level, which is a high cost process. Recent advances are moving toward conducting packaging at the wafer level.
6. **Testing and Characterization Equipment.** Testing and Characterization Equipment provides testing and analyses of the photonic integrated device. It is an essential part of quality control and is leveraged during the testing process.
7. **Cleanroom Facilities.** Cleanroom Facilities are designed to maintain very low levels of contaminants. Surface functionalization will likely generally be conducted in cleanroom environments.
8. **Optical Power Meter**: An optical power meter measures power in optical signals. It is used during calibration.
9. **Alignment and Positioning Equipment**: Alignment and positioning equipment aligns machine components and moving parts. It is used during calibration.
10. **Photodetectors**: Photodetectors sense light and other radiation, and would be used during calibration.
11. **Photonic Wire Bonding**: Photonic wire bonding is a variant of additive

manufacturing; it is to optical system assembly what metal wire bonding is to electronics. Photonic wire bonding can be used during packaging.

12. **Microarray Printers**: Microarray printers are used to print assays onto devices. They are used during the deposition process.

Table 10, below, depicts what component of the photonic integrated device development process each piece of equipment or work context relates to.

Table 10. Equipment by Part of the Manufacturing Process

Component of the Process	Equipment or Work Context Examples
Fabrication	Photolithography Equipment Deposition Equipment Etching Equipment
Testing	Testing and Characterization Equipment
Packaging	Packaging and Assembly Equipment Photonic Wire Bonding
Deposition	Microarray Printers
Calibration	Optical power meter; alignment and positioning equipment; photodetectors
Microfluidics for Analyte Delivery	Cleanroom Facilities

While equipment exists to automate and expedite the process of developing photonic integrated devices, one of the experts we interviewed noted that a lot can be done by hand, emphasizing that the human finger is quicker and more sensitive than an automated robot (Expert Interviews, 2024).

With respect to the work context for these technicians, they are likely to work in environments where they are working in parallel with other technicians rather than in fully collaborative processes (Expert Interviews, 2024). That is, they are likely to have specific roles in producing photonic integrated devices that are conducted in sequence rather than multiple technicians collaborating on the exact same part of the production process (Expert Interviews, 2024).

As a result, each unique technician position is expected to have implications for other roles and positions, but the workers in these positions will conduct work generally independently (Expert Interviews, 2024). It therefore helps for all technicians to know a little about every step of the process, so they can best do their own jobs, but they will predominantly stick to and develop expertise in their specific part of the process (Expert Interviews, 2024). Notably, technicians will need to learn their specific role for their specific organization, and these roles may vary across organizations given that the process for creating photonic integrated devices varies tremendously across organizations. For example, some photonic integrated devices may be created through fabricating, functionalizing, and then packaging, whereas others are fabricated, packaged, and then functionalized. Depending on the specific protocol for a particular work environment, each technician will need to learn to complete their tasks slightly differently.

In work contexts where technicians are completing their work more manually, with less reliance on machines, the ability to communicate across areas of expertise becomes particularly important. That is, assay specialists, engineers, and data scientists will all need to be conversational enough with each others' expertise to effectively communicate across specialties and create an integrated final product (Expert Interviews, 2024).

Education & Certifications Needed

Subject matter experts universally shared that, as expected, creator and innovator workforces must have PhDs (Expert Interviews, 2024). And, initial workforces in smaller companies prior to reaching manufacturing tend to be multidisciplinary, drawing experts from a variety of different backgrounds (Expert Interviews, 2024). The part of the workforce that focuses on design is expected to need at least a bachelor's level education; often, those involved in design still do have PhDs (Expert Interviews, 2024). Correspondingly, photonics education to date has predominantly emerged in advanced degree programs (Moore et al., 2023). This is consistent with education related to nanotechnology in general (Yawson, 2010).

During the initial phase into manufacturing, technicians might need to have a bachelor's or master's degree if not a PhD (Expert Interviews, 2024, Yawson, 2010). To the extent that a facility creating bio-photonic integrated devices continues to produce them more manually, this is expected to continue. One expert compared production volume of semiconductors (1 unit a month) to production volume of glasses (100,000 a day) as an explanation for why some companies working with bio-photonic integrated devices may continue to rely on a highly skilled and educated workforce in production (Expert Interviews, 2024). Market matters.

However, at full-scale manufacturing, technicians will generally not need to have such advanced degrees (Expert Interviews, 2024, Yawson, 2010). Essentially, the higher the volume of manufacturing, the lower the degree needed. Subject matter experts repeatedly noted that much of what an individual technician will do, they will need to learn on the job (Expert Interviews, 2024). Experts do note that technicians should be interested in and familiar with:

- Photonics
- Mechanics
- Software
- Fluidics
- Biochemistry or chemistry
- Engineering
- Materials science
- Data science

Less than a college degree (certificate or associate's level degree) is expected to be sufficient for a photonic integrated device technician. Materials science and biochemistry/chemistry are particularly critical for technicians in functionalization roles, but not as critical for PIC Technicians (Expert Interviews, 2024). In other words, the educational needs for Functionalization Technicians may be higher for PIC Technicians. However, this is most likely to be true for Functionalization Technicians working on more manual processes. Functionalization Technicians operating machines to complete their work may not need as much education - for these technicians, their job may be predominantly to maintain the machine, ensuring that it runs during the day without issues, and to fill bottles (Expert Interviews, 2024). One expert opined that having at least one photonics class is helpful, not because it develops the knowledge and skills needed to be successful, but because it is an indicator of interest in the field (Expert Interviews, 2024).

Some experts noted that while some background is helpful, what is learned in school gets lost and experience from comparable industries can be more important than education (Expert Interviews, 2024). One of the people we spoke to estimated that up to

80% of a technician's skills from their prior job translated to their work with photonic integrated devices (Expert Interviews, 2024). Others shared a preference for hiring their workforce straight out of receiving their education both to keep costs down and to train them for the specific processes used in their organization (Expert Interviews, 2024). These experts noted that shop floor employees tend to be very specialized and difficult to replace (Expert Interviews, 2024). Regardless of initial skills and experience at hire, the overwhelming majority of our interviews highlighted how important on-the-job learning is and therefore how important retention is for these positions (Expert Interviews, 2024). Some of the experts we spoke to noted that technicians in their workforce have been the most stable talent (Expert Interviews, 2024).

Important points on education required include:

- The process for creating a bio-photonic integrated devices varies so much, much of what needs to be learned will be trained on the job - essentially, technicians may follow an apprenticeship model
- It can take up to 3-5 years to train a technician, and most training is practice based
- Strong hires may come directly from school, or from comparable roles in PC industries
- Materials science and biochemistry/chemistry are essential for Functionalization Technicians
- Higher volume production requires a less educated workforce than lower volume production
- Retention is critical - one expert shared that people can stay in the field for 20-30 years

Education & Certifications Available

Currently, very few programs exist related to photonic integrated devices. A review of Lightcast provided associate degree level programs graduating at least 6 people a year for laser and optical technology technicians. These programs are:

- Cincinnati State Technical and Community College, Cincinnati, Ohio
- Front Range Community College, Westminster, Colorado
- Hillsborough Community College, Tampa, Florida
- Indian Hills Community College, Iowa, Wapello

- Indian River State College, Fort Pierce, Florida
- MIAT College of Technology, Canton, Michigan
- Monroe Community College, Rochester, New York
- Springfield Technical Community College, Springfield, Massachusetts

There are also certificates available in photonics, including:

- Stonehill College, Easton, MA, Photonics and Optical Engineering
- Quinsigamond Community College, Worcester, MA, Electronics Engineering Technology - Photonics Certificate

And, there is some graduate level programming available on photonic integrated devices, including:

- Duke University, Durham, NC, Photonics
- Tufts, Medford, MA, Master's in Biophotonics
- Rochester, Rochester, NY, Master's in Optics
- University of Central Florida, Orlando, FL, Applied Photonics, Optical Imaging Systems
- University of Colorado Boulder, Boulder, CO, Photonics and Optics

Additionally, AIM Photonics offers a week-long summer academy at MIT on photonic circuit design, chip fabrication, packaging, testing, and system applications.

One of the experts we spoke to in interviews recommended that at some point in the development process - perhaps toward TRL/MRL 9 - companies begin reaching out and engaging with youth education to bolster interest in the product (Expert Interviews, 2024). In the area of photonic integrated devices specifically, some work has just begun to introduce photonics to students earlier in their learning. For example, the Spark Photonics Foundation is a nonprofit organization that introduces students from kindergarten through high school to semiconductors and photonics technology.

Finally, SPIE (n.d.) offers a variety of free training materials on optics and photonics, including: introduction to advanced manufacturing and photonics, analog & digital electronics, tools and testing, tools for advanced manufacturing and photonics, statistical process control in photonics and automation, introduction to applied optics, introduction to fiber optics, and photonic integrated circuits.

Recruiting and Hiring Guidance

As noted repeatedly in expert interviews, the majority of what a technician needs to do is learned on the job (Expert Interviews, 2024). What a technician needs upon entry is an openness to learning, excellent control of their fingers (“fingerspitzengefühl”), resilience, and patience (Expert Interviews, 2024). Experts note that prior knowledge in optics is not required (Expert Interviews, 2024). It may be useful to have some prior knowledge and experience with machinery, but even this is not required (Expert Interviews, 2024). The one area where prior knowledge may be helpful is prior chemistry or biochemistry knowledge and experience for functionalization technicians (Expert Interviews, 2024). However, even this is truly only needed for smaller scale, more manual production. Full scale production using machines will not require this prior knowledge for even Functionalization Technicians.

When recruiting into the technician roles, there are two routes a production company may take. The first is recruiting from parallel and contributing industries or competitors, where they exist (Expert Interviews, 2024). Doing so would ensure some level of background knowledge in photonic integrated device manufacturing or similar manufacturing processes. However, since each company is expected to follow its own unique practices, a large amount of upskilling is still expected to be required when recruiting from other organizations (Expert Interviews, 2024). Recruiting from other organizations is likely to be a more effective tactic early in the MRL/TRL lifecycle, when technicians still need to be more educated and skilled in order to support in the development of the processes that will eventually become standardized. When recruiting from other companies, organizations may use placement companies, or more standard job search boards such as Linkedin or Indeed (Expert Interviews, 2024). Experts note that the workforce for technicians is currently small, and can be very mobile, so offering competitive salaries and effectively keeping employees can be a challenge (Expert Interviews, 2024). This is particularly true for production companies based in smaller towns and cities, who often report being reliant on an international pool of talent rather than having success with local talent, who are more likely to stay (Expert Interviews, 2024).

Alternatively, organizations may hire lower-skilled individuals who are directly out of a certificate or two-year degree (or equivalent) and train them internally (Expert Interviews, 2024). Consistent with this perspective, Kirchain and his colleagues note in a recent industry report on the manufacturing workforce in photonics that the photonics industry is seeing an increase in demand for technical workers, especially in jobs like Photonics Technicians, Electrical/Electronic Engineering Technicians, and CNC Machine Tools Operators (Kirchain, Moore, Field, Saini, & Westerman, 2021). The authors recommend that to recruit effectively, companies should focus on these high-demand roles by highlighting career growth opportunities and working with schools to ensure a steady flow of skilled workers (Kirchain et al., 2021). The training programs from which they hire would ideally concentrate on hands-on, specialized learning in key areas like fabrication, test design, troubleshooting, and teamwork, and may also include new skills like using digital tools and advanced statistics to help workers keep up with the industry's changing needs (Kirchain et al., 2021).

This is likely to be a particularly effective solution for hiring into technician roles who manufacture bio-photonic integrated devices at scale, using predominantly machines. These individuals will need to be trained nearly entirely internally. Based on the specificity of each organization’s operations and the need to train technicians on sight, full scale manufacturing would likely benefit most from an apprenticeship program. Until the external training infrastructure for 2-year degrees and certificates specifically around bio-photonic integrated devices is fully built up, bio-photonic integrated device companies will likely find success recruiting from local community colleges and engaging those they hire in apprenticeships to existing technicians. Internal hands-on training supplemented by courses as needed (particularly around safety) can be used to upskill these new hires. Those who pass a one- or two-year apprenticeship, for example, might receive a promotion into a photonic integrated device technician role.

With respect to hiring technicians to produce bio-photonic integrated devices, it is likely that traditional hiring tools (e.g., resume review, interviews) will not consistently optimally identify the best talent. The attributes that are needed at entry are more related to dexterity and motivation. Accordingly, resume review and interviews may be predominantly useful when hiring from competitors and PC technology organizations, and largely for more highly skilled jobs. Interviews for photonic integrated device technician roles should focus more on attributes related to conscientiousness, dependability, and motivation, if they are used at all.

Additionally, organizations hiring technicians may wish to implement one or both of two other selection devices. The first is known as a realistic job preview (RJP). An RJP exposes candidates interested in a particular job to the conditions relevant to that job. At times, RJPs can be administered by video. Other times they are conducted on purpose. An RJP is helpful in circumstances where the conditions of the job may pose a retention risk. Experts repeatedly noted that not everyone is willing to work in the conditions of a manufacturing facility, which may feel tedious and arduous (Expert Interviews, 2024). This is exactly the circumstance under which an RJP can be effective. Properly implemented, an RJP provides a realistic glimpse into the life of a technician, and enables potential candidates to proceed with the selection process (or opt out) with full knowledge of what the working environment will entail. According to Breaugh (2009), implementing a Realistic Job Preview (RJP) is straightforward and easily communicated to managers, employees, and recruits. RJPs are cost-effective compared to other turnover-focused strategies. In addition, both theory and research support their effectiveness in reducing voluntary turnover while improving new employee performance and job satisfaction (Breaugh, 2009).

Experts also repeatedly noted that finger sense and finger control are essential for photonic integrated device technicians, even more so than for those working with microelectronics (Expert Interviews, 2024). Physical capabilities such as these are difficult if not impossible to assess during interview processes. However, organizations might use work samples to assess candidates' dexterity. Hunter and Hunter (1984) highlight that work samples are highly effective in predicting job performance, especially for roles requiring specific skills or physical abilities. These tests directly assess relevant competencies, indicating how well a candidate might perform on the job. Specifically, organizations hiring photonic integrated device technicians may create simple tasks that require dexterity to complete. They can demonstrate how to complete the task, then ask each candidate to replicate the process. Work samples are the clearest path to assessing physical capabilities. However, they can be time consuming and expensive to conduct (Hunter and Hunter, 1984), and it is absolutely essential that each candidate is presented with the exact same task. It can therefore be not only time consuming to run each candidate through the work sample, but also time consuming to set up the work sample exactly the same way each time.

Training and Onboarding

The majority of what a technician needs to know that is specific to photonic integrated device manufacturing they will learn on the job. This is partially due to the large variability in purpose, design, and production processes for different photonic integrated devices (Expert Interviews, 2024).

Experts note that what is needed for success and what needs to be trained may also vary by the size of the company employing the technician (Expert Interviews, 2024). For example, technicians working at smaller companies will likely require more cross training and fill more roles than technicians working at larger companies (Expert Interviews, 2024). A theme in our interviews was the importance of cross-disciplinary education and training, especially for companies employing more manual processes and operating with smaller teams (Expert Interviews, 2024).

The experts we spoke to shared that the cross-disciplinary training that supports this level of communication is not currently widespread (Expert Interviews, 2024). Some biomedical engineering and materials science training at the undergraduate level may provide some of this training (Expert Interviews, 2024). However, many fields are more siloed and do not provide in particular the quantitative aspects of materials science (Expert Interviews, 2024). Thus, most hires will come in with experience in one necessary part of the work but not others, necessitating a different training focus for different people hired into technician roles even at the same company (Expert Interviews, 2024). One expert noted, for example, that hires with a chemistry background may understand safety procedures, but may not know how to conduct quality control using a particular machine (Expert Interviews, 2024). Regardless of prior experience or background, every new hire is expected to need upskilling.

Training should be predominantly hands-on. Certain topics may be appropriately supplemented with formal training materials or courses, such as chemical handling and safety procedures. However, most of the training required is best achieved - according to all experts - through learning by doing (Expert Interviews, 2024). Typically, more expert-level and experienced employees will need to train new technicians.

As previously mentioned, an apprenticeship model works well for this form of training. By coupling one or more new technicians with more experienced workers, technicians are able to learn while still contributing to the process and minimizing costly errors. Intentional onboarding that assigns new technicians to an identified senior employee to accomplish set goals over a three month onboarding period can speed up the training process by standardizing it and providing accountability.

Tasks that will be part of the focus at training, that is, critical and necessary tasks that are not needed are entry are listed below.

PIC Technician tasks to train on:

- Assemble equipment or components
- Set up equipment
- Prepare industrial materials for processing or use
- Operate industrial processing or production equipment
- Adjust equipment to ensure adequate performance
- Test performance of equipment or systems
- Test characteristics of materials or products
- Measure physical characteristics of materials, products, or equipment
- Monitor operations to ensure adequate performance
- Regularly inspect and maintain equipment to ensure safe operation
- Analyze performance of systems or equipment

- Document technical designs, procedures, or activities
- Maintain operational records
- Maintain electronic, computer, or other technical equipment
- Specify, coordinate, or conduct quality control or quality assurance programs or procedures
- Train others on operational or work procedures

Functionalization Technician tasks to train on:

- Assemble equipment or components
- Set up equipment
- Prepare industrial materials for processing or use
- Operate laboratory or field equipment
- Adjust equipment to ensure adequate performance
- Mix, pour, or use processing chemicals or gasses according to safety standards or established operating procedures.
- Test performance of equipment or systems
- Test characteristics of materials or products
- Measure physical characteristics of materials, products, or equipment
- Measure physical or chemical properties of materials or substances
- Prepare specimens or materials for surface functionalization
- Inspect or measure thin films of carbon nanotubes, polymers, or inorganic coatings, using a variety of techniques or analytical tools
- Monitor laboratory work to ensure compliance with set standards
- Regularly inspect and maintain equipment to ensure safe operation
- Analyze biological or chemical substances or related data to improve operations
- Document technical designs, procedures, or activities
- Maintain operational records

- Specify, coordinate, or conduct quality control or quality assurance programs or procedures
- Train others on operational or work procedures
- Ensure use of proper personal protective equipment (PPE) including but not limited to safety glasses or goggles and gloves

Key skills and competencies that should be part of the focus of training - that is, critical skills and competencies that are not needed on day one - are listed below.

Skills to train on:

- Equipment maintenance
- Material Handling
- Operation and Control
- Operations Monitoring
- Problem Solving Skills
- Quality Control Analysis
- Safety Compliance
- Science
- Systems Analysis
- Technical Proficiency

Competencies to train on:

- Compliance
- Equipment
- Quality Control
- Technology
- Technological Expertise

All photonic integrated device technicians will require training in a variety of these areas. In particular, Moore et al. (2023) note that training should focus on fabrication and assembly, testing, and troubleshooting. However, functionalization technicians will require more training and education in chemistry and safety procedures related to handling chemicals and working in a clean room environment (Expert Interviews, 2024).

Particular areas of focus for all photonic integrated device technician training will include:

1. Safety

Safety training is expected to vary. First, working with different compounds and materials may require specialized training protocols (Expert Interviews, 2024). Second, eye safety will be needed due to the use of lasers (Expert Interviews, 2024). In some instances, when technicians need to work with gas, they may need body gear for safety as well (Expert Interviews, 2024). Safety training should be among the very first training offered to new technicians. Functionalization Technicians will require safety training related to working with chemicals and biological materials.

2. Processes

Since each organization will follow a unique process, and operate with a unique workforce structure, the specific processes for which a technician will be responsible will likewise vary considerably across companies. Technicians should receive a high-level introduction to the entire process required to create a photonic integrated device. Then, technicians should receive training in running the processes for which they are responsible. Functionalization Technicians will need specific training around their role in the functionalization process, which may include chemical preparation of the wafer, applying thin film coatings, and/or activation of antibodies on the surface of the wafer, among other activities (Expert Interviews, 2024).

Particular emphasis should be paid to processes related to quality control, which will enable technicians to check for the quality of their work output rather than relying on more senior colleagues to spot mistakes (Expert Interviews, 2024). Technicians will also need to be trained on how to assess if processes are yielding desired results, or if they need to be altered to do so (Expert Interviews, 2024).

3. Equipment

The equipment that technicians will use is expected to vary based on company size, orientation toward segmentation, and specific role (Expert Interviews, 2024). The equipment used to manufacture photonic integrated devices is very delicate and expensive, and technicians must adapt quite quickly (Expert Interviews, 2024). Each technician will need training on the specific equipment they will need to use in their organization and role. Technicians will also need to be trained on how to assess whether equipment is working appropriately (Expert Interviews, 2024).

4. Testing

Testing methodologies will also vary (Expert Interviews, 2024). New technicians will need to receive specialized training around how to run and interpret the results of tests of the photonic integrated devices they produce (Expert Interviews, 2024).

5. Data

All technicians will require a basic understanding of how to interpret data. The data provided, and their role in the process, will again depend on how their specific organization works. The data that come from the use of photonic integrated devices should follow a specific function, depending on what the sensor is designed to detect (Expert Interviews, 2024). Data science for photonic integrated devices is therefore different from traditional statistics (Expert Interviews, 2024). Determining if the sensor is functioning properly will require a unique analytical ability that is not typically taught in prior coursework (Expert Interviews, 2024). The data analytics skills required for this may be descriptive and specialized. In order to determine if a device is functioning properly, and communicate what may not be working properly, technicians will need specialized data training specific to the machines, sensors, and data analytics leveraged in their organization (Expert Interviews, 2024).

Implications for Role Development

Technicians working with equipment to manufacture photonic integrated devices will be expected to work in highly specialized roles conducting very routinized processes. They will need to be very consistent in the execution of their work. According to one of the experts we interviewed, a technician's work must be done at a certain rhythm, like a dance, to achieve consistent results (Expert Interviews, 2024). They will need to essentially work as one with the machines they use (Expert Interviews, 2024).

Monotonous and formalized or routine jobs have been found to contribute to boredom at work, which has a variety of negative impacts on both individuals and organizations (Loukidou, Loan-Clarke, & Daniel, 2009). Similarly, repetitive work can lead to stress (Garde, Hansen, & Jensen, 2003; Lundberg et al., 1989). Garde et al. further suggested that people engaging in repetitive work demanding a high degree of attention may not be as precise. This would have profound implications for the production of photonic integrated devices, which require a great deal of precision to manufacture effectively.

Breaks are an essential component of creating a work environment where repetition does not lead to negative outcomes for individual workers or organizations. Fostering social connection through gameplay and humor can help counteract the potential negative impacts of monotony and routine in the workplace (Loukidou et al., 2009). Additionally, cognitive tasks between bouts of repetitive work can accelerate recovery with some markers of fatigue (Mathiaseen, Hallman, Lyskov, & Hygge, 2014).

In terms of break frequency, Dababneh, Swanson, and Shell (2001) found that giving meat-processing plant workers 9 minute breaks every 51 minutes had no negative impact on productivity, and improved lower extremity discomfort. Workers also preferred 9-minute breaks every 51 minutes to 3 minute breaks every 27 minutes, suggesting that extremely frequent breaks may not be as effective or appealing. Similarly, Tsao, Kim, Ma, and Nussbaum (2021) found that longer and self-selected breaks, as opposed to short breaks, are preferred by workers and resulted in less muscle fatigue. Again, taking breaks did not negatively impact performance. The authors suggest a self-selected schedule specifically for repetitive precision tasks. Finally, Tucker (2003) notes that breaks can also reduce accident risk, and notes that micro-breaks can be beneficial beyond the more common practice of breaks every two hours.

In summary, with technicians engaging in repetitive, precise work, it is encouraged that:

- Breaks be implemented to enable fatigue recovery and reduce accident risk
- Breaks be implemented at least every two hours, possibly for nine minutes out of every hour or self-scheduled
- Technicians be allowed to engage in cognitive tasks during breaks (this may involve sequencing more cognitive work to occur during break times)
- Technicians be encouraged to connect socially through gameplay or humor during breaks

Implications for Leadership

Technician supervisors will have the responsibility of ensuring technicians develop the skills necessary to complete their required tasks, including reinforcing the importance of communication across disciplines (Expert Interviews, 2024). One of the experts we spoke to in our interviews noted that technicians have critical shop floor experience that can inform the development and improvement of each product, and that it is important to involve even the technician workforce in providing feedback to improve product design (Expert Interviews, 2024).

This idea is similar to the management approach offered by Rother (2009) in his book, Toyota Kata. According to Rother (2009), Toyota’s success has been driven by their management philosophy, which trains frontline employees - technicians - to raise actionable suggestions on production and product improvement. In this approach to managing, leaders focus on developing the way technicians think (judgment and decision making, troubleshooting) to help them detect opportunities to improve both process and product by identifying a target future and moving toward it. This improvement kata focuses energy on discovery to uncover obstacles and enable the generation of creative solutions to moving past these obstacles. It requires adaptation and curiosity. Notably, Moore et al. (2023) recommended that workforce training programs focus on the ability to recommend changes to process and design - this is perfectly in line with the philosophy behind Toyota Kata.

Finally, a MWP would ideally contain guidance and information on the number of technicians needed to manufacture the emerging technology as well as information regarding the career paths for technicians. However, the manufacturing of photonic integrated devices is not yet far enough along for us to have clear insights into these two components of workforce development and preparation. As one potential benchmark for workforce size, Moore et al. (2023) estimated that the United States photonics industry would need at least 42,000 new middle-skilled technical workers by 2030. We do expect that the career pathway for technicians will be specialized. As such, we expect that people who become technicians may begin in easier positions (one expert noted truck drivers as one such position) and then get trained to enter technician positions (Expert Interviews, 2024).

Based on our interviews with experts, it appears that more advanced production for photonic integrated sensors is TRL/MRL/WRL 6, corresponding to system/subsystem model or prototype demonstration in a relevant environment and the capability to produce a prototype system or subsystem in a production relevant environment. From a workforce perspective, this means that much of the workforce directly producing photonic integrated devices at the moment are specialist innovator workforces (Conducere-MIT Collaboratory, 2024). These workforces are still characterized by higher educated workers and the beginning of role differentiation as tasks begin to be assigned to individuals. To move to WRL 7, additional work will be needed to differentiate the skills and competencies that are essential for production in high-production environments (using equipment, for example) versus in low-production environments, where work is conducted more manually. While we have made some progress in differentiating between what we call technician and technologist roles, further differentiation may be required. Additionally, while we have begun to identify what is needed at day one, organizations moving toward TRL/MRL/WRL 7 will need to firmly identify the tasks, skills, and competencies needed at day one, and begin to identify training needs and resources.

Appendix A: Biographies of Team Members

The team for this MWP consisted of consultants from Conducere Consulting, the Massachusetts Institute of Technology (MIT) Materials Systems Laboratory, and the Microphotonics Center and Materials Research Laboratory.

Juliet Aiken

Juliet Aiken, PhD, serves as the Head of Consulting at Conducere. With a background in organizational psychology, she specializes in future focused workforce planning, aligned strategic change management, and research and data analytics. She serves as a trusted advisor to help organizations pivot during periods of uncertainty, supporting them in developing talent management systems and in conducting strategic and workforce planning processes. She specializes particularly in partnering with client teams to drive change while simultaneously building internal capacity to carry organizational development and workforce planning related changes forward. Aiken has over a decade of experience in consulting and leadership roles in government, private sector, and nonprofit sectors, including work as an expert witness in compensation disparity and disparate treatment cases. Aiken is part of the team that won the 2017 Innovation in Assessment Award from IPAC for "Hiring Quickly and at a Low Cost under a Consent Decree." She also received the 2020 Society for Industrial Organizational Psychology (SIOP) Early Career Award in Practice and the 2024 Blacks in I/O Psychology Inaugural Ally Champion Award. Aiken earned her PhD and a Certificate in Statistics and Measurement from the University of Maryland.

jaiken@conducerellc.com

Anuradha Argarwal

Dr. Anu Agarwal is a Principal Research Scientist at MIT's Microphotonics Center and Materials Research Laboratory. Her work has focused on the technologies for the foundational components of electronic-photonic chips including polysilicon waveguides, LEDs, couplers, photodetectors, and optical buffers. As the leader of the AIM Academy LEAP at MIT since January of 2018, she has and continues to (i) build a roadmap document of photonic sensors through the Integrated Photonic Systems Roadmap - International (IPSR-I) and World Technology Roadmap Forum (WTRF), by identifying technology gaps in materials, components and systems for photonic sensors, and (ii) enable education and workforce development in integrated photonics across the workforce supply chain from K-Gray. As the director of Electronic-Photonic Packaging (EPP) at MIT's Microphotonics Center, she is exploring innovative photonic testing and packaging solutions. As a part of this work and others, Anu was named a 2022 Optica Fellow with over 250 journal and refereed conference publications, 17 awarded patents, and 4 pending patents.

Prior to coming to MIT she received her doctoral degree in Electrical Engineering from Boston University, where she investigated the spatial extent of point defect interactions in silicon. With Dr. Agarwal's cross-disciplinary training, industrial experience, and background in Physics, Electrical Engineering, and Materials Science, she has successfully connected basic sciences with relevant applications, using integrated devices that are manufacturable on a large scale.

anu@mit.edu

Autumn Fedewa

Autumn Fedewa serves as a junior consultant at Conducere. Her background covers both the public and nonprofit sectors, where she's been involved in creating inclusive leadership competency models, supporting strategic change management initiatives, integrating new technologies, and leveraging people analytics to drive change in organizations. Fedewa has experience training global teams on adopting new technologies. She's also been pivotal in helping organizations refine job descriptions through detailed job analysis. Autumn holds a Master's degree in Industrial/Organizational Psychology.

apfedewa@gmail.com

Frank R. Field

Dr. Frank Field is an MIT Institute for Data, Sys-tems, and Society (IDSS) Senior Research Engineer, the MIT Material Systems Lab Research Director, and the Interim Director for the MIT Technology and Policy Program (TPP). Frank is a researcher in the area of ma-terials systems analysis, a field in which economic and operations research methods are applied to problems in materials and materials processing and manufacturing. His research has focused upon the practical application of these methods, and the thrust of this work has been to develop ways in which systems analysis tools, combined with materials process engineering knowledge, can be intelligently applied to address important issues in prod-uct development and production planning, and in their associated areas of public and private policy. Frank's work has been applied to materials and manufacturing problems in the automotive, aerospace, electronics, and resource extraction industries.

furd@mit.edu

Taylor Jordan

Taylor serves as a junior consultant at Conducere. She has supported clients navigating crucial organizational shifts centered around inclusion. Taylor has done so through the execution of organizational diagnosis, innovative job design, and the strategic establishment of affinity groups. She is experienced in data analytics, particularly in the realm of job analysis, where she integrates insights into impactful data presentations. Taylor holds a Master’s degree in Industrial/Organizational Psychology.

taylorj@conducerellc.com

Elizabeth A. Moore

Dr. Elizabeth Moore is a Research Scientist with the Materials Systems Laboratory and the Concrete Sustain-ability Hub at MIT. Her research investigates the envi-ronmental, economic, and workforce challenges posed by emerging technology systems. Her current research areas include life cycle assessment and techno-economic mod-eling, analysis of mineral and commodity markets, and assessment of workforce needs for key emerging technolo-gies and industries.

eamoore@mit.edu

Randolph Kirchain

Dr. Randolph Kirchain is a Principal Research Sci-entist with the MIT Materials Research Laboratory and the Director of the MIT Concrete Sustainability Hub. Dr. Kirchain’s research and teaching explores the impact of technology decisions on the economic and environ-mental performance of manufacturing and the systems in which they are produced, used, and eventually dis-carded. His research informs the implications of tech-nology decisions through the development of methods to model two critical aspects of technological performance: 1) life cycle economics and 2) systemwide sustainability.

kirchain@mit.edu

Beth Unger

Dr. Unger is a dynamic individual with a diverse skill set and a passion for making a positive impact on the world. With a master’s and Ph.D. in environmental science from the University of Iceland, she brings a distinctive international perspective. She has extensively studied the European energy markets, the utilization of various vehicle fuel types, including hydrogen and electricity, and transportation safety. Currently, as a distinguished research scientist at MIT, her work focuses on workforce development across multiple industries, including concrete, advanced manufacturing, photonics, and semiconductors. Beth is dedicated to developing transformative solutions that enhance productivity, increase satisfaction, and expand candidate pools and ensuring there is a strong alignment between industry needs and classroom learning objectives.

eunger@mit.edu

Appendix B: References and Resources

Agarwal, J. Hu, J. Michon, M. Shalaginov (2020). Photonic Integrated Sensors: Circuits. https://buildyourfuture.us/courses/course-v1:AIM_Academy+PICS+2021

AIM Photonics. AIM Photonics Boot Camp. https://www.aimphotonics.com/photonics-bootcamp

Arthur, W., Doverspike, D., Kinney, T. B., & O'Connell, M. (2017). The impact of emerging technologies on selection models and research: Mobile devices and gamification as exemplars. In Handbook of employee selection (pp. 967-986). Routledge.

Breaugh, J. A. (2009). Realistic job previews. In The handbook of industrial and organizational psychology (Chapter 8). Wiley. https://doi.org/10.1002/9780470592663.ch27

Breaugh, J. A. (2017). The contribution of job analysis to recruitment. The Wiley Blackwell handbook of the psychology of recruitment, selection and employee retention, 12-28.

Campion, M. A., Fink, A. A., Ruggeberg, B. J., Carr, L., Phillips, G. M., & Odman, R. B. (2011). Doing competencies well: Best practices in competency modeling. *Personnel psychology, 64(1),* 225-262. doi: 10.1111/j.1744-6570.2010.01207.x

Conducere-MIT Collaboratory (2024). Workforce Readiness Level (WRL) Deskbook.

Dababneh, A. J., Swanson, N., & Shell, R. L. (2001). Impact of added rest breaks on the productivity and well being of workers. Ergonomics, 44(2), 164–174. https://doi.org/10.1080/00140130121538

Expert Interviews (2024). Appendix C.

Garde, A. H., Hansen, A. M., & Jensen, B. R. (2003). Physiological responses to four hours of low-level repetitive work. Scandinavian Journal of Work, Environment & Health, 29, 452-460.

Han, Z., Lin, P., Singh, V., Kimerling, L., Hu, J., Richardson, K., Agarwal, A., & Tan, T. H. (2016). On-chip mid-infrared gas detection using chalcogenide glass waveguide. *Applied Psychics Letters, 108,* 141106. doi: 10.1063/1.4945667

Hodgkinson, J. & Tatam, R. P. (2012). Optical gas sensing: A review. *Measurement Science and Technology, 24,* 012004. doi: 10.1088/0957-0233/24/1/012004

Hu, J., Carlie, N., Feng, N., Petit, L., Agarwal, A., Richardson, K., & Kimerling, L. (2008). Planar waveguide-coupled, high-index-contrast, high-Q resonators in chalcogenide glass for sensing. *Optics Letters, 33,* 2500-2502. doi: 10.1364/OL.33.002500

Hunter, J. E., & Hunter, R. F. (1984). Validity and utility of alternative predictors of job performance. Psychological Bulletin, 96(1), 72-98. https://doi.org/10.1037/0033-2909.96.1.72

Kirchain, R., Moore, E., Field, F. R., Saini, S., & Westerman, G. (2021). Preparing the advanced manufacturing workforce: A study of occupation and skills demand in the photonics industry.

Kita, D. M., Miranda, B., Favela, D., Bono, D., Michon, J., Lin, H., Gu, T., & Hu, J. (2018). High-performance and scalable on-chip digital Fourier transform spectroscopy. Nature communications, 9(1), 4405. doi: 10.1038/S41467-018-06773-2

Lightcast (data accessed 2024). https://lightcast.io/

Lin, H., Luo, Z., Gu, Tan, Kimerling, L. C., Wada, K., Agarwal, A., & Hu, J. (2018). Mid-infrared integrated photonics on silicon: A perspective. *Nanophotonics, 7,* 393-420. doi: 10.1515/NANOPH-2017-0085

Lin, P. T., Giammarco, J., Borodinov, N., Savchak, M., Singh, V., Kimerling, L. C., Tan, D. T., H., Richardson, K. A., Luzinov, I., & Agarwal, A. (2015). Label-free water sensors using hybrid polymer–dielectric mid-infrared optical waveguides. *ACS Applied Materials & Interfaces, 7(21),* 11189-11194. doi: 10.1021/ACSAMI.5b01013

Lin, P., Singh, V., Cai, Y., Kimerling, L., & Agarwal, A. (2013). Air-clad silicon pedestal structures for broadband mid-infrared microphotonics. *Optics Letters, 38,* 1031-1033. doi: 10.1364/OL.38.001031

Lin, P. T., Singh, V., Wang, J., Lin, H., Hu, J., Richardson, K., Musgraves, J. D., Luzinov, I., Hensley, J., Kimerling, L. C., & Agarwal, A. (2013). Si-CMOS compatible materials and devices for mid-IR microphotonics. Optical Materials Express, 3(9), 1474-1487. doi: 10.1364/OME.3.001474

Loukidou, L., Loan-Clarke, J., & Daniel, K. (2009). Boredom in the workplace: More than monotonous tasks. International Journal of Management Reviews, 11, 381-405. doi: 10.1111/j.1468-2370.2009.00267.x

Luan, E., Shoman, H., Ratner, D. M., Cheung, K. C., & Chrostowski, L. (2018). Silicon Photonic Biosensors Using Label-Free Detection, *Sensors, 18, 3519*. doi: 10.3390/s18103519

Lundberg, U., Granquvist, M., Hansson, T., Magnusson, M., & Wallin, L. (1988). Psychological and physiological stress responses during repetitive work at an assembly line. Work & Stress, 3, 143-153. doi: 10.1080/02678378908256940

Mathiassen, S. E., Hallman, D. M., Lyskov, E., & Hygge, S. (2014). Can cognitive activities during breaks in repetitive manual work accelerate recovery from fatigue? A controlled experiment. PloS one, 9(11), e112090.

Moore, E. A., Field, F. R., & Kirchain, R. (2024). Occupation Clustering Methodology for Training In-Demand Engineering Technician Skills in the Advanced Manufacturing Industry. *Journal of Engineering Technology,* 34-46.

National Center for O*NET Development. (2021). ONET OnLine*. https://www.onetonline.org

National Center for Optics and Photonics Education (OP-TEC) (2016). Integrated Photonics. OP-TEC, University of Central Florida.

Moore, E. A., Field, F. R., Saini, S., Roth, R., Kimerling, L. C., Westerman, G., & Kirchain, R. (2023). Adaptable middle-skilled labor: a neglected roadblock to photonics industry growth. *Applied Optics, 62,* 9-16. doi: 10.1364/AO.488960

Oderkerk, B. (2016). Exploring the Limitation of Physics: Physics Miniaturization of spectrometers, the sensitivity/resolution tradeoff. *Optik & Photonik, 11(5),* 45-47. doi: 10.1002/OPPH.201600037

Office of the Executive Director for Systems Engineering and Architecture (2023). Technology Readiness Assessment Guidebook. https://www.cto.mil/wp-content/uploads/2023/07/TRA-Guide-Jun2023.pdf

Office of the Secretary of Defense Manufacturing Technology Program (2022). Manufacturing Readiness Level (MRL) Deskbook. https://www.dodmrl.com/MRL_Deskbook_2022__20221001_Final.pdf

Resnick, A. (2023). How to Prepare for a Career in Optics and Photonics. https://spie.org/news/preparing-for-a-career-in-optics-and-photonics#_=_

Robinson-Morral, E. J., Hendrickson, C., Gilbert, S., Myers, T., Simpson, K., & Loignon, A. C. (2018). Practical considerations for conducting job analysis linkage exercises. Journal of Personnel Psychology, 17(1), 12.

Rother, M. (2009). Toyota kata. New York, NY: McGraw-Hill Professional Publishing.

Sakar, D., Jamal, I., & Mitra, S. (2013). Analysis, design and fabrication of optical waveguides for Mach-Zehnder Interferometry, *Optics Communications, 311,* 338-345. doi: 10.1016/J.OPTCOM.2013.08.079

Shahbaz, M., Butt, M. A., & Piramidowicz, R. (2023). A Concise Review of the Progress in Photonic Sensing Devices. *Photonics, 698.* doi: 10.3390/photonics10060698

Singh, V., Lin, P. T., Patel, N., Lin, H., Li, L., Zou, Y., Deng, F., Ni, C., Hu, J., Giammarco, J., Soliani, A. P., Zdrykos, B., Luzinov, I., Novak, S., Novak, J., Wachtel, P., Dantos, S., Musgraves, J. D., Richardson, K., Kimerling, L. C., & & Agarwal, A. M. (2014). Mid-infrared materials and devices on a Si platform for optical sensing. *Science and technology of advanced materials, 15(1),* 014603. doi: 10.1088/1468-6996/15/1/014603 P.T.

Singh, R., Su, P., Kimerling, L., Agarwal, A., & Anthony, B. W. (2018). Towards on-chip mid infrared photonic aerosol spectroscopy. *Applied Physics Letters,* 113(23). doi: 10.1063/1.5058694

SPIE (no date). Photonics Technician Training. https://spie.org/education/technician-resources/photonicstechnicianprogram#_=_

Steglich, P., Rabus, D. G., Sada, C., Paul, M., Weller, M. G., Mai, C., & Mai, A. (2022). Photonic Micro-Ring Resonators for Chemical and Biological Sensing: A Tutorial. *Sensors Journal, 22,* 10089–10105. doi: 10.1109/JSEN.2021.3119547

Tsao, L., Kim, S., Ma, L., & Nussbaum, M. A. (2021). An exploratory study comparing three work/rest schedules during simulated repetitive precision work. Ergonomics, 64(12), 1579–1594. https://doi.org/10.1080/00140139.2021.1950844

Tucker, P. (2003). The impact of rest breaks upon accident risk, fatigue and performance: A review. Work & Stress, 17(2), 123–137. https://doi.org/10.1080/0267837031000155949

United States Office of Personnel Management (2013). Multipurpose Occupational Systems Analysis Inventory - Close-Ended (MOSAIC) Competencies. https://www.opm.gov/policy-data-oversight/assessment-and-selection/competencies/mosaic-studies-competencies.pdf

Yawson, R. M. (2010). Skill needs and human resources development in the emerging field of nanotechnology. Journal of Vocational Education and Training, 62(3), 285-296.

Appendix C: Interview Process Summary

We conducted interviews at first with academic experts, followed by industry professionals. Our goal was at first to determine what our area of focus would be within photonic integrated devices, then to determine parallel products and contributing technologies. In our interviews with experts we also inquired about their opinions on what is unique about the photonic integrated devices workforce, in particular for middle skilled technicians.

Interviews began on 11/28/2023 and ended on 5/7/2024. In total, we reached out to 46 experts. Of those 46 contacts, we held interviews with 24.

- 5 interviews with six academic or research experts
- 20 interviews with industry leaders

Note that one industry leader served a dual role in academia. Of the industry leaders interviewed:

- Seven were Chief Executive Officers (CEOs)
- Four occupied other senior positions (CCO, CMO, CTO, Managing Director)
- Three were in roles related to innovation and research and development
- Two were in roles related to venture support and business development
- Two were in roles related to education, the workforce, or human capital
- One managed engineering directly

Each interview unfolded slightly differently, depending on the specific experiences and insights of the expert we spoke to. Interview questions included, but were not limited to the following:

- What are different types or applications of photonic integrated devices?
- How (in what ways) do they vary from one another?
- What stage of technology development are photonic integrated devices in? Where is the product more advanced, and where is it less advanced?
- What are the biggest challenges or opportunities for the application of photonic integrated device technology right now?
- What are the biggest challenges or opportunities for the development of photonic integrated device technology right now?

- What are some of the challenges and opportunities regarding the skills and knowledge needed to design this technology? What about manufacturing it?

- What problems do photonic integrated devices solve? Why are they being developed?

- What prompted you to begin manufacturing photonic integrated devices? What problem will your devices solve?

- What were some of the key manufacturing challenges you faced when beginning to produce photonic integrated devices? How did you overcome them?

- What is the process by which photonic integrated devices manufactured?

- What materials, processes, and people are involved in manufacturing photonic integrated devices?

- What job roles are involved in manufacturing integrated photonic technologies? What does each do, at a high level? (Probe why some roles are split, or combined)

- What workforce challenges have you faced, either in hiring or training, in manufacturing integrated photonic integrated devices?

A total of 584 statements across these interviews were content-coded. Content was coded to reflect:

- Product (photonic integrated devices, electronics, product comparison, etc.)

- Workforce discussed (creator, transition, manufacturing)

- Job type the comment referenced (design, technician, or, where differentiating between two technician roles, functionalization or PIC technician)

- Category of information provided (e.g., skill, competency, market, roles, education, tasks, training, etc)

Coding was conducted via an iterative process, as no existing coding scheme for MWPs has been created to date. Coding categories emerged from the interviews, and the researchers continually refined coding categories to ensure all comments were captured as succinctly and effectively as possible. In addition to the observations shared throughout this document, we note the following findings from our interviews:

- Product
  - The overwhelming majority of comments focused on photonic integrated devices specifically (93%)
  - 6% focused on comparisons between photonic integrated devices and other products or technologies
- Workforce Discussed
  - Almost one third (30%) of the statements applied directly to the creator workforce
  - Only 3% of expert comments addressed the needs of the workforce that transitions between creation/prototyping and manufacturing
  - Just over half (53%) of comments addressed the manufacturing workforce specifically
- Job Type
  - 20% of expert comments applied specifically to design-related work
  - 23% of expert comments applied to technician roles broadly
  - 19% of comments were specific only to the role we have labeled “Functionalization Technician”
  - 6% of comments were specific only to the role we have labeled “PIC Technician”
- Category. Experts shared a wide variety of insights, including insights on:
  - The evolving market (19% of comments)
  - The design features of Photonic Integrated Devices (17% of comments)
  - Tasks in creating Photonic Integrated Devices (13% of comments)
  - Roles that will produce Photonic Integrated Devices (11% of comments)
  - Education requires (11% of comments)

- Skills, competencies, and workforce conditions (9% of comments)
- Background required, including prior experiences (6% of comments)
- Training required (6% of comments)
- Workforce availability (5% of comments)
- Equipment (4% of comments)