IMPROVING FLUID POWER COMPONENTS AND SYSTEMS FOR INDUSTRIAL APPLICATIONS

TABLE OF CONTENTS

IMPROVING FLUID POWER COMPONENTS AND SYSTEMS FOR INDUSTRIAL APPLICATIONS

BACKGROUND AND INTRODUCTION

The National Fluid Power Association (NFPA) is a trade association representing the U.S. hydraulics and pneumatics industry. Its more than 300 member companies represent all segments of the fluid power supply and value chain, and it engages in numerous outreach programs to machine builders in fluid power's many mobile and industrial customer markets.

NFPA first published its *Technology Roadmap for the Fluid Power Industry* in 2009, describing an industry-wide consensus regarding the pre-competitive research and development needs associated with improving the design, manufacture, and function of fluid power components and systems. Under the guidance of NFPA's Roadmap Committee, the document has been refreshed and republished multiple times, most recently in 2023.

NFPA's Technology Roadmap, and the research and development agenda it describes, has been focused on advancements that will help the fluid power industry meet the future needs of its customers, expand into new markets, and attract the best and brightest students to the field.

It is used by the NFPA and its academic partners to guide their research efforts, by NFPA members and other industry players to inform decisions about research partnerships and product development, and by academic, government, and other organizations that wish to pursue research and development projects of importance to the fluid power industry.

It is also a key part of NFPA's fluid power technology promotion strategy, as it illuminates places both where fluid power meets the needs of its customers and where emerging technologies are being developed and deployed.

With the publication of this new document in 2025, NFPA will begin producing two Technology Roadmaps – this one specifically for fluid power in industrial applications, and a second Roadmap, scheduled for publication in 2027, specifically for fluid power in mobile applications. This is in recognition of the unique needs associated with these two different kinds of machine builders.

NFPA's Roadmap Committee established an Industrial Technology Task Force, comprised of interested parties across the fluid power supply and value chain, that worked via email, conference call, and virtual meeting from December 2024 to November 2025 to complete this report. Although the report contains information regarding the consensus and individual opinions of the Task Force members, and represents their most up-to-date thinking on the state-of-the-art, the report should not be interpreted as the single or wholly comprehensive agenda for the fluid power industry.

IMPROVING FLUID POWER COMPONENTS AND SYSTEMS FOR INDUSTRIAL APPLICATIONS

The 2025 NFPA Industrial Technology Roadmap is a tool that can be used, with permission obtained from NFPA, by organizations that wish to pursue projects of importance to the fluid power industry. These organizations include both research institutions and companies across the fluid power supply and value chain. By aligning their activities with the challenges, objectives, and proposed projects described in this Roadmap, they will all play a role in positively shaping the future of fluid power technology.

By putting forth this Roadmap, representing a broad consensus of industry players, and focused on pre-competitive initiatives that will help develop new technologies to benefit the industries, markets, and people served by fluid power, NFPA demonstrates a commitment both to collaboration and to long-term growth and sustainability.

ROADMAP ELEMENTS

The 2025 NFPA Industrial Technology Roadmap is comprised of five primary elements, each connected to the next in an interdependent chain.

1. **Customer Drivers** are the top-level performance objectives of fluid power customers, the OEMs or machine builders that manufacture machines that often incorporate fluid power systems. Customer Drivers help these machine builders serve the needs of their own customers and are not necessarily connected to their use of fluid power.

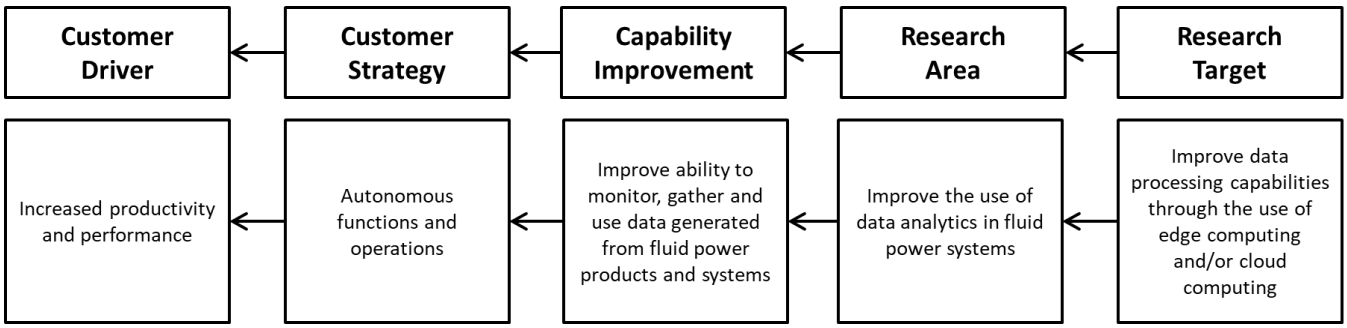
2. **Customer Strategies** are the machine-level objectives and technologies that the machine builders have set or are using to help them achieve the top-level performance objectives described by the Customer Drivers. Again, these Customer Strategies are not necessarily connected to their use of fluid power.

3. **Capability Improvements** describe the ways in which fluid power systems must improve if they are to participate or increase their participation in the technology trends described by the Customer Strategies.

4. **Research Areas** are the broad areas of pre-competitive investigation that could assist in bringing about the Capability Improvements.

5. **Research Targets** are the objectives that quantify or otherwise describe successful strategies for pursuing the Research Areas.

EXAMPLE:



ROADMAP UPDATE PROCESS AND TIMELINE

The following process and timeline were used to update and produce the 2025 NFPA Industrial Technology Roadmap.

Phase 1 – Planning and Development (4Q24)

Dec 2024	Task force meeting to review project plan and survey on Customer Drivers and Strategies

Phase 2 – Customer Drivers and Strategies (1Q25)

Jan 2025	Launch of survey on Customer Drivers and Strategies
Feb 2025	Deadline to respond to survey on Customer Drivers and Strategies
Mar 2025	Task Force meeting to discuss, define and prioritize Customer Drivers and Strategies, and to review survey on Fluid Power Alignment and Capability Improvements
	Meeting report published with prioritized Customer Drivers and Strategies

Phase 3 – Capability Improvements (2Q25)

Apr 2025	Launch of survey on Fluid Power Alignment and Capability Improvements
May 2025	Deadline to respond to survey on Fluid Power Alignment and Capability Improvements
Jun 2025	Task Force meeting to discuss, define and prioritize Capability Improvements, and to review survey on Research Areas and Targets
	Meeting report published with prioritized Capability Improvements

Phase 4 – Research Areas and Targets (3Q25)

Jul 2025	Working Groups identified for each Capability Improvement
	Launch of survey on Research Areas and Targets
Aug 2025	Deadline to respond to survey on Research Areas and Targets
	Working Group meetings to discuss and prioritize Research Areas for each Capability Improvement

Sep 2025 Task Force meeting to review, harmonize and prioritize Research Areas and Targets

Meeting report published with prioritized Research Areas and Targets

Phase 5 – Final Roadmap Document (4Q25)

Oct 2025 Draft Roadmap written and circulated for review and comment

Nov 2025 Deadline to return comments on draft Roadmap

Final Roadmap published and presented

INDUSTRIAL CUSTOMER MARKETS

Fluid power technology is used in hundreds of applications in dozens of specific customer markets. NFPA groups fluid power's customer markets into two general areas: (1) Applications for different types of mobile or off-highway equipment; and (2) Applications for different types of industrial, stationary or in-plant equipment.

For the purpose of identifying the Customer Drivers and Strategies of this Industrial Technology Roadmap, the following fourteen large industrial customer markets were defined.

- **Aerospace Manufacturing.** In-plant machines and equipment used in the manufacture of aerospace products and parts.
- **Food Product Machinery.** In-plant machines and equipment that process raw ingredients into food products.
- **Medical Equipment Manufacturing.** Stationary equipment that creates tools, instruments and equipment that are used in healthcare.
- **Metalworking and Machine Tools.** Stationary equipment used to cut or shape metal or metal parts.
- **Oil and Gas Machinery.** Machinery used to extract oil and/or process it into gasoline.
- **Packaging Machinery.** In-plant machines and equipment used to pack products for storage, shipping, or sale.
- **Plastics and Rubber Machinery.** Stationary equipment used to process or make plastic or rubber products.
- **Power Generation.** Stationary equipment used to generate power, including through such clean energy technologies as solar, wind, and wave.
- **Primary Metals Manufacturing.** Stationary equipment used to extract, refine, and shape raw materials into metal products.
- **Recycling Equipment.** Stationary equipment that transforms waste into reuseable resources.
- **Robotics, Assembly and Material Handling.** Stationary machines and equipment that move materials through a facility or perform assembly tasks.
- **Semiconductor Machinery.** In-plant machines used to fabricate semiconductor chips, test them, and support their manufacturing process.
- **Vehicle Manufacturing.** In-plant machines and equipment used in the manufacture of both on- and off-highway vehicles.
- **Wood and Paper Machinery.** Stationary equipment used to process wood or paper products.

CUSTOMER DRIVERS

Customer Drivers are the top-level performance objectives of fluid power customers, the OEMs or machine builders that manufacture machines that often incorporate fluid power systems. Customer Drivers help these machine builders serve the needs of their own customers and are not necessarily connected to their use of fluid power.

At its March 2025 meeting, the NFPA Industrial Technology Task Force reviewed the results of a January 2025 survey conducted by NFPA to determine the market drivers and technology strategies important to the fourteen industrial markets. The survey received responses from 146 individuals across the fluid power supply and value chain, including a large percentage from the NFPA Industrial Technology Task Force.

Based on the results of the 2023 NFPA Technology Roadmap and a subsequent discussion with the NFPA Industrial Technology Task Force, survey responders were asked to rank the importance of each of the following Customer Drivers for each of the Industrial Markets with which they were familiar.

Customer Drivers
Machine builders want to provide their customers with machines that offer:

- Increased availability and up-time.
- Increased productivity and performance.
- Lower total cost of ownership.
- Compliance with regulations.
- Sustainability.

Importance of Existing Customer Drivers

Some variations in importance emerged for individual markets. In the aggregate, 96% of the driver choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

IMPROVING FLUID POWER COMPONENTS AND SYSTEMS FOR INDUSTRIAL APPLICATIONS

		CUSTOMER DRIVERS						
INDUSTRIAL MARKETS	N	Increased availabilty and up time	Increased productivity and performance	Lower total cost of ownership	Compliance with regulations	Sustainability		
Aerospace Manufacturing	26	4.462	4.462	3.500	4.462	3.308	5	Extremely important
Food Product Machinery	46	4.435	4.304	3.652	4.304	3.283	4	Very important
Medical Equipment Manufacturing	15	4.400	4.533	3.533	4.933	3.267	3	Somewhat important
Metalworking and Machine Tools	57	4.386	4.544	3.842	3.491	2.842	2	Not so important
Oil and Gas Machinery	37	4.622	4.378	3.405	4.189	3.162	1	Not at all important
Packaging Machinery	30	4.400	4.533	4.100	3.533	3.367		
Plastics and Rubber Machinery	21	4.571	4.381	4.095	3.476	3.381		5.000 - 4.566
Power Generation	24	4.542	4.250	3.792	4.083	3.500		4.565 - 4.131
Primary Metals Manufacturing	17	4.529	4.706	3.882	3.471	2.824		4.130 - 3.695
Recycling Equipment	15	4.600	4.400	4.267	3.667	3.667		3.694 - 3.260
Robotics, Assembly and Material Handling	33	4.667	4.788	4.061	3.515	3.121		3.259 - 2.824
Semiconductor Machinery	4	5.000	5.000	3.500	4.250	3.000		
Vehicle Manufacturing	34	4.647	4.706	4.118	3.971	3.382		
Wood and Paper Machinery	21	4.381	4.524	3.810	3.238	2.905		
Other*	7	4.286	4.286	4.286	4.143	3.571		
All Respones	387	4.506	4.501	3.837	3.871	3.204		

*Seven responders suggested that other industrial markets be considered. These were described as: (1) Construction; (2) Department of Defense; (3) Marine, Ships, Oil Rigs, Windmills, Hydraulics and Enclosures; (4) Medical Devices; (5) Mining; (6) Mobile Machines; and (7) Testing.

For all markets, and for the aggregate of all responses, “Increased availability and up time” and “Increased productivity and performance” were the two most important drivers. “Lower total cost of ownership” and “Compliance with regulations” rated as highly important for some individual markets.

Most Important Customer Driver

Respondents were also asked to identify the most important Customer Driver in each of the customer markets with which they were familiar. The color codes categorize the most popular responses – with dark green representing the driver most frequently chosen as the most important and light green representing the driver second most frequently chosen as the most important driver.

INDUSTRIAL MARKETS	N	CUSTOMER DRIVERS					
		Increased availabilty and up time	Increased productivity and performance	Lower total cost of ownership	Compliance with regulations	Sustainability	Other*
Aerospace Manufacturing	26	19%	31%	8%	23%	4%	15%
Food Product Machinery	43	37%	30%	7%	23%	2%	0%
Medical Equipment Manufacturing	15	13%	13%	20%	53%	0%	0%
Metalworking and Machine Tools	55	20%	67%	7%	2%	0%	4%
Oil and Gas Machinery	36	53%	39%	6%	0%	0%	3%
Packaging Machinery	29	21%	59%	21%	0%	0%	0%
Plastics and Rubber Machinery	21	43%	29%	24%	0%	5%	0%
Power Generation	23	57%	26%	4%	4%	9%	0%
Primary Metals Manufacturing	17	29%	53%	18%	0%	0%	0%
Recycling Equipment	15	27%	47%	20%	0%	7%	0%
Robotics, Assembly and Material Handling	32	28%	63%	3%	6%	0%	0%
Semiconductor Machinery	3	67%	33%	0%	0%	0%	0%
Vehicle Manufacturing	32	28%	44%	19%	6%	3%	0%
Wood and Paper Machinery	21	29%	48%	24%	0%	0%	0%
Other	7	29%	29%	14%	14%	0%	14%
All Respones	375	31%	44%	12%	8%	2%	2%

Most popular choice
Second most popular choice
Third most popular choice

*Six responders suggested other drivers as the most important. These were described as: (1) Customer service; (2) Environmental and cost avoidance; (3) Initial purchase price; (4) Protect internal parts from corrosion and contamination; (5) Reliability; and (6) Technical support.

Several markets saw a broad distribution of drivers thought to be the most important. For almost all markets, “Increased availability and uptime” or “Increased productivity and performance” were selected as the most important driver by large majorities of responders.

Identification of Customer Drivers for the 2025 Industrial Technology Roadmap

Several additional suggestions for Customer Drivers were made by the survey responders. Reviewing this quantitative and qualitative information at its March 2025 meeting, the NFPA Industrial Technology Task Force prioritized the following Customer Drivers for the 2025 Industrial Technology Roadmap.

Customer Drivers

Machine builders want to provide their customers with industrial machines that offer:

- **Increased availability and up-time.** Generally defined as the robustness of the machine, its ability to work continuously.
- **Increased productivity and performance.** Generally defined as the efficiency of the machine, its ability to do more work in less time.
- **Compliance with regulations.** Such as those pertaining to environmental, safety, or other concerns.
- **Lower total cost of ownership.** Includes capital and/or operating costs.

CUSTOMER STRATEGIES

Customer Strategies are the machine-level objectives and technologies that the machine builders have set or are using to help them achieve the top-level performance objectives described by the Customer Drivers. Again, these Customer Strategies are not necessarily connected to their use of fluid power.

At its March 2025 meeting, the NFPA Industrial Technology Task Force reviewed the results of a January 2025 survey conducted by NFPA to determine the market drivers and technology strategies important to the fourteen industrial markets. The survey received responses from 146 individuals across the fluid power supply and value chain, including a large percentage from the NFPA Industrial Technology Task Force.

Based on the results of the 2023 NFPA Technology Roadmap and a subsequent discussion with the NFPA Industrial Technology Task Force, survey responders were asked to rank the importance of each of the following Customer Strategies for each of the Industrial Markets with which they were familiar.

Customer Strategies
Machine builders are using these objectives or technologies to deliver the top-level performance objectives of their machines.

- **Automation.** Either semi- or full-autonomous functions and/or operations.
- **Compactness.** Increasing power density and/or reducing weight and/or size.
- **Connectivity.** Expanding the use of data, such as intelligence for cloud-based condition monitoring, integration with site management systems, and/or communicating machine status for other value-added purposes.
- **Energy Efficiency.** Increasing it; and including strategies to extend operational life, use less energy, and/or reduce emissions.
- **Maintenance.** Making it easier; and including strategies to ease the serviceability of the machine and to increase the availability of repair or replacement parts.
- **Materials.** Use of conflict and/or environmentally friendly materials in strategic ways to better comply with regulations.
- **Noise.** Reducing perceived noise levels and/or improving noise pulsation.
- **Precision Control.** The ability to manage a system or process with high accuracy and minimal error.

<u>Importance of Existing Customer Strategies</u>

Some variations in importance emerged for individual markets. In the aggregate, 91% of the strategy choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

INDUSTRIAL MARKETS	N	CUSTOMER STRATEGIES: Automation	Compactness	Connectivity	Energy Efficiency	Maintenance	Materials	Noise	Precision Control
Aerospace Manufacturing	25	3.720	3.480	3.720	3.680	4.160	3.640	3.480	4.520
Food Product Machinery	46	4.130	3.152	3.543	3.391	4.065	3.457	3.022	3.913
Medical Equipment Manufacturing	15	4.267	3.467	4.067	3.400	4.267	3.600	3.667	4.600
Metalworking and Machine Tools	56	4.196	3.036	3.571	3.411	4.143	2.875	3.196	4.304
Oil and Gas Machinery	37	3.432	3.054	3.216	3.459	4.378	3.108	2.622	3.622
Packaging Machinery	30	4.467	3.400	3.867	3.533	4.100	3.167	3.267	4.167
Plastics and Rubber Machinery	21	3.857	3.000	3.333	3.714	3.810	2.762	3.143	4.048
Power Generation	24	3.750	3.167	3.583	3.750	4.292	3.083	3.083	4.042
Primary Metals Manufacturing	17	4.059	2.765	3.706	3.706	4.353	2.824	2.941	4.176
Recycling Equipment	15	3.600	3.067	2.933	3.667	4.267	2.667	3.200	3.400
Robotics, Assembly and Material Handling	33	4.485	3.788	4.091	3.606	4.242	3.030	3.455	4.455
Semiconductor Machinery	4	4.500	3.250	3.750	4.000	4.250	3.750	3.250	4.750
Vehicle Manufacturing	34	4.118	3.294	3.912	3.706	4.059	3.206	3.500	4.235
Wood and Paper Machinery	21	3.762	2.714	3.238	3.238	3.952	2.762	2.762	3.952
Other*	7	3.714	3.571	3.429	3.429	4.000	3.429	3.286	4.286
All Respones	385	4.021	3.203	3.610	3.540	4.153	3.119	3.169	4.127

5	Extremely important
4	Very important
3	Somewhat important
2	Not so important
1	Not at all important
	4.750 - 4.325
	4.324 - 3.899
	3.898 - 3.473
	3.472 - 3.047
	3.046 - 2.622

*Seven responders suggested that other industrial markets be considered. These were described as: (1) Construction; (2) Department of Defense; (3) Marine, Ships, Oil Rigs, Windmills, Hydraulics and Enclosures; (4) Medical Devices; (5) Mining; (6) Mobile Machines; and (7) Testing.

For most markets, and for the aggregate of all responses, “Automation,” “Maintenance,” and “Precision Control” were the three most important strategies. “Connectivity” and “Energy Efficiency” rated as highly important for some individual markets.

Most Important Customer Strategy

Respondents were also asked to identify the most important Customer Strategy in each of the customer markets with which they were familiar. The color codes categorize the most popular responses – with dark green representing the strategy most frequently chosen as the most important and light green representing the strategy second most frequently chosen as the most important strategy.

INDUSTRIAL MARKETS	N	CUSTOMER STRATEGIES								
		Automation	Compactness	Connectivity	Energy Efficiency	Maintenance	Materials	Noise	Precision Control	Other*
Aerospace Manufacturing	24	8%	4%	8%	4%	17%	8%	0%	46%	4%
Food Product Machinery	42	43%	0%	0%	2%	21%	12%	2%	14%	5%
Medical Equipment Manufacturing	15	20%	0%	20%	0%	13%	7%	7%	33%	0%
Metalworking and Machine Tools	54	35%	0%	0%	2%	19%	2%	0%	41%	2%
Oil and Gas Machinery	36	17%	0%	0%	8%	64%	0%	0%	8%	3%
Packaging Machinery	28	61%	7%	11%	7%	4%	0%	0%	11%	0%
Plastics and Rubber Machinery	21	24%	0%	5%	14%	24%	14%	0%	19%	0%
Power Generation	24	13%	4%	4%	29%	38%	0%	0%	13%	0%
Primary Metals Manufacturing	17	24%	0%	6%	12%	24%	0%	0%	35%	0%
Recycling Equipment	15	33%	0%	0%	20%	47%	0%	0%	0%	0%
Robotics, Assembly and Material Handling	32	41%	3%	6%	6%	3%	0%	6%	34%	0%
Semiconductor Machinery	3	0%	0%	0%	0%	0%	0%	0%	100%	0%
Vehicle Manufacturing	31	13%	0%	6%	29%	13%	0%	0%	39%	0%
Wood and Paper Machinery	20	20%	0%	0%	5%	45%	0%	0%	30%	0%
Other	7	29%	14%	14%	0%	14%	0%	0%	14%	14%
All Respones	**369**	28%	2%	4%	9%	24%	3%	1%	26%	2%

Most popular choice
Second most popular choice
Third most popular choice

*Six responders suggested other strategies as the most important. These were described as: (1) Availability of suitable parts at a reasonable price; (2) Electrification; (3) Manufacturing location (USA); (4) Proper surface treatment that keep components clean after years of use, cost, availability; (5) Safety; and (6) Specification and legal compliance.

Several markets saw a broad distribution of strategies thought to be the most important. For almost all markets, “Automation,” “Precision Control,” or “Maintenance” were selected as the most important strategy by large majorities of responders.

Identification of Customer Drivers for the 2025 Industrial Technology Roadmap

Several additional suggestions for Customer Strategies were made by the survey responders. Reviewing this quantitative and qualitative information at its March 2025 meeting, the NFPA Industrial Technology Task Force prioritized the following Customer Strategies for the 2025 Industrial Technology Roadmap.

Customer Strategies

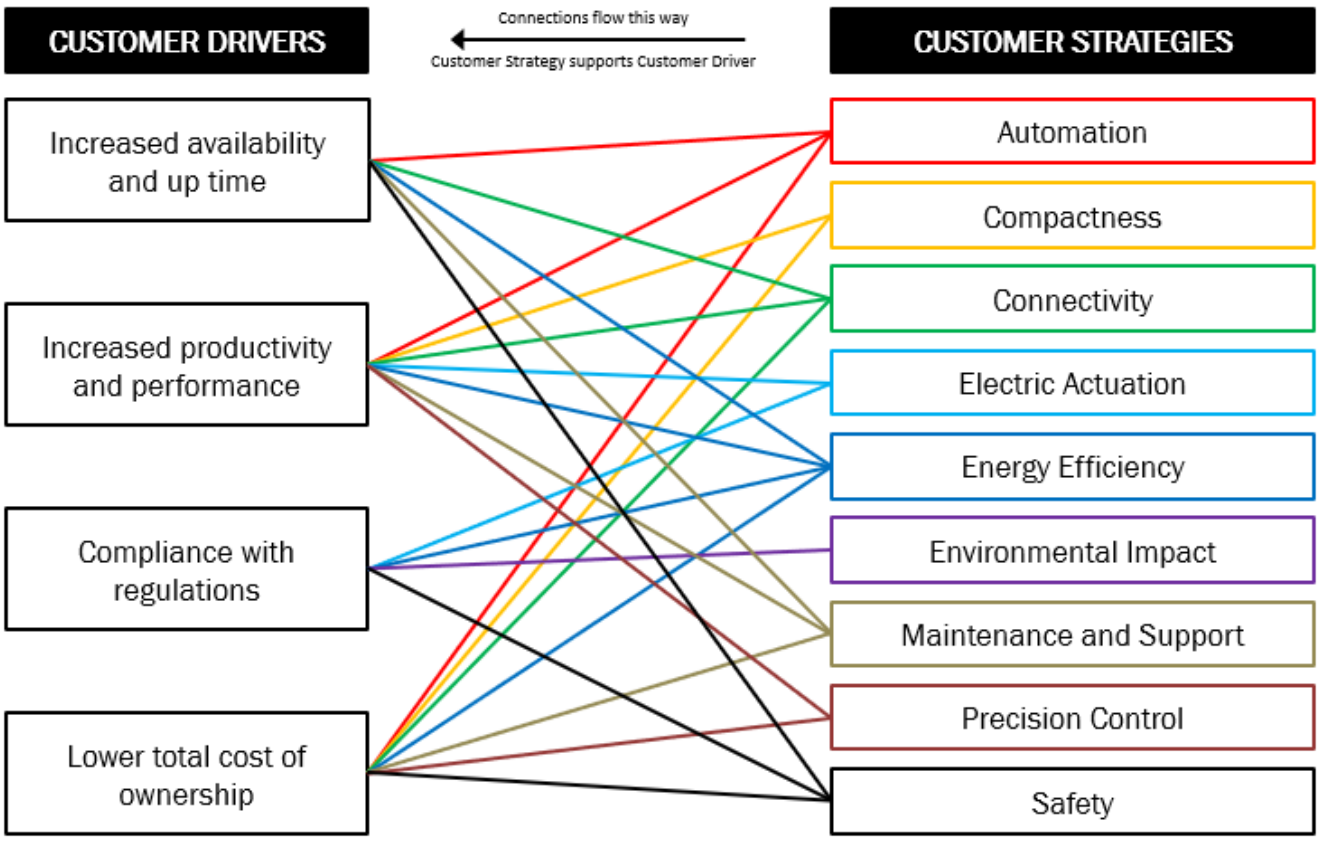
Machine builders are using these objectives or technologies to deliver the top-level performance objectives of their industrial machines:

- **Automation.** Incorporating either semi or fully autonomous functions and/or operations on the machine.
- **Compactness.** Increasing the power density of the machine without increasing its weight and/or size.
- **Connectivity.** Expanding the use of data, such as intelligence for cloud-based condition monitoring, integration with site management systems, and/or communicating machine status for other value-added purposes.
- **Electric Actuation.** Moving towards electric actuation to improve efficiency or control on the machine.

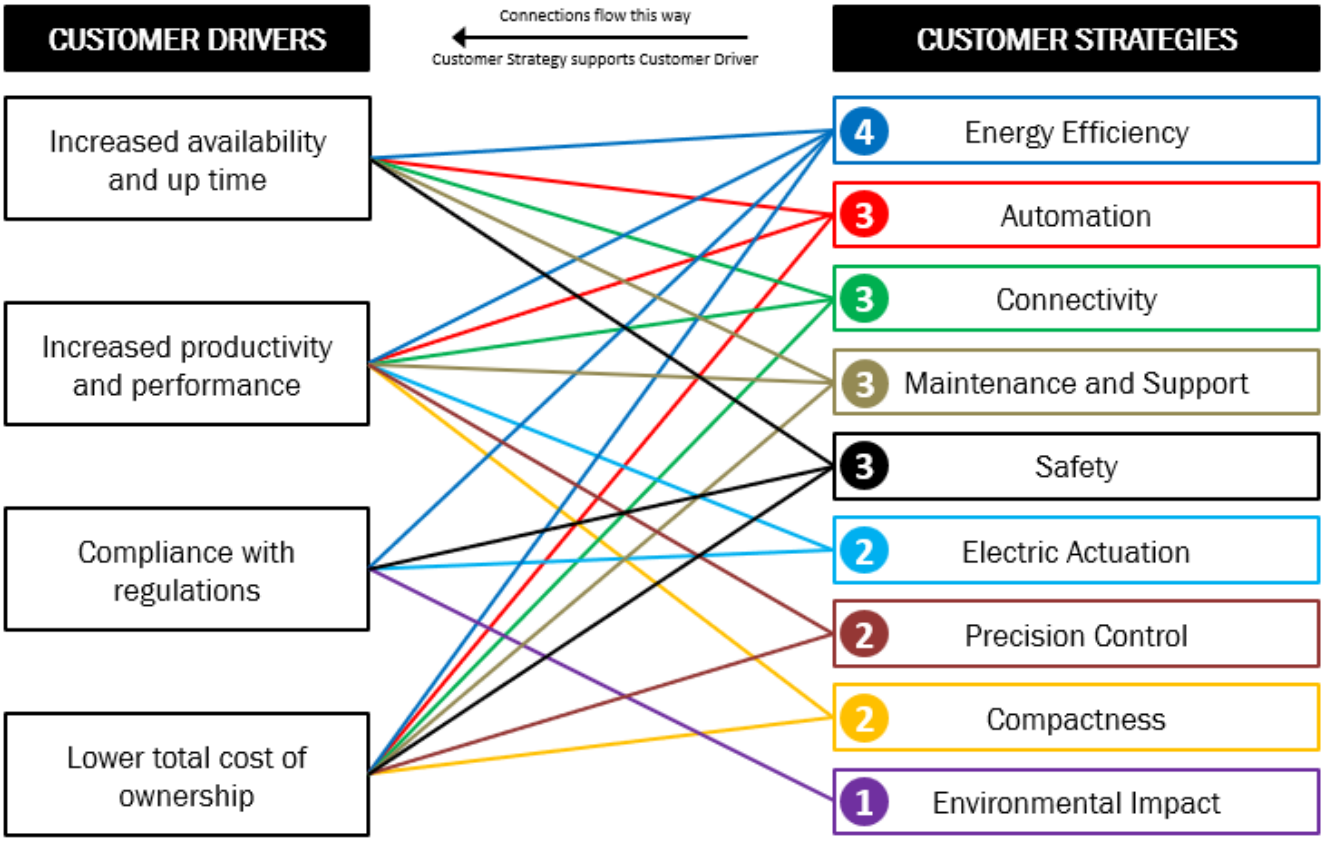
- **Energy Efficiency.** Increasing energy efficiency, including strategies to extend operational life, use less energy, and/or reduce emissions.
- **Environmental Impact.** Reducing environmental impact, including strategies to lower noise, reduce leaks and/or use environmentally safe fluids.
- **Maintenance and Support.** Making it easier to maintain the machine, including strategies to ease initial integration and implementation, to provide documentation support, to ease the serviceability of the machine, and to increase the availability of repair or replacement parts.
- **Precision Control.** Improving the ability to manage systems or processes on the machine with high accuracy and minimal error, including through the use of sensors.
- **Safety.** Improving the safe use of the machine.

Connections to Customer Drivers

The Task Force discussed possible connections between the prioritized Customer Strategies and Customer Drivers, recognizing that each strategy could be used to help the machine builder achieve multiple drivers. A map of these connections is shown below:



Prioritizing the Customer Strategies by the number of Customer Drivers they could impact results in the following connection map:



FLUID POWER'S ALIGNMENT WITH CUSTOMER STRATEGIES

At its June 2025 meeting, the NFPA Industrial Technology Task Force reviewed the results of two April 2025 surveys conducted by NFPA to determine fluid power's current ability to meet the customer needs described by the Customer Strategies. One survey asked about hydraulic alignment; the other about pneumatic alignment. Together, the surveys received responses from 119 individuals across the fluid power supply chain, including a large percentage from the NFPA Industrial Technology Task Force.

Survey participants were asked how important each of the Customer Strategies were to the technology and performance objectives of the machine builders in the industrial markets with which they were familiar, and they were asked how frequently either hydraulics or pneumatics were included as part of each strategy. The scoring scale was: 5 = Extremely important or Always; 4 = Very important or Usually; 3 = Somewhat important or Sometimes; 2 = Not so important or Rarely; 1 = Not at all important or Never.

		HYDRAULICS		
CUSTOMER STRATEGIES	N	IMPORTANCE	FREQUENCY	GAP
Automation	74	3.973	3.608	-0.365
Compactness	68	3.412	3.412	0.000
Connectivity	66	3.545	3.212	-0.333
Electric Actuation	64	3.547	3.406	-0.141
Energy Efficiency	62	3.677	3.645	-0.032
Environmental Impact	61	3.148	3.180	0.033
Maintenance and Support	62	4.000	4.081	0.081
Precision Control	61	4.131	3.934	-0.197
Safety	60	4.250	4.117	-0.133
All Responses	578	3.740	3.614	-0.126

	4.250 to 4.023
	4.022 to 3.809
	3.808 to 3.589
	3.588 to 3.368
	3.367 to 3.148

CUSTOMER STRATEGIES	N	PNEUMATICS IMPORTANCE	PNEUMATICS FREQUENCY	PNEUMATICS GAP
Automation	21	4.286	3.952	-0.333
Compactness	18	3.833	3.611	-0.222
Connectivity	14	4.071	3.857	-0.214
Electric Actuation	13	3.692	3.538	-0.154
Energy Efficiency	12	3.417	3.583	0.167
Environmental Impact	12	2.917	3.083	0.167
Maintenance and Support	12	3.917	3.917	0.000
Precision Control	12	4.167	3.833	-0.333
Safety	12	4.250	4.250	0.000
All Responses	126	3.873	3.746	-0.127

4.286 to 4.012
4.011 to 3.738
3.737 to 3.465
3.464 to 3.191
3.190 to 2.917

In the aggregate, 94% of the strategy choices were rated as at least somewhat important, and fluid power was used at least sometimes for 100% of the strategies. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

When we aggregate the hydraulic and pneumatic responses and order the chart from most to least important Customer Strategy, we see the results shown below.

CUSTOMER STRATEGIES	N	FLUID POWER IMPORTANCE	FLUID POWER FREQUENCY	FLUID POWER GAP
Safety	72	4.250	4.139	-0.111
Precision Control	73	4.137	3.918	-0.219
Automation	95	4.042	3.684	-0.358
Maintenance and Support	74	3.986	4.054	0.068
Connectivity	80	3.638	3.325	-0.313
Energy Efficiency	74	3.635	3.635	0.000
Electric Actuation	77	3.571	3.429	-0.143
Compactness	86	3.500	3.453	-0.047
Environmental Impact	73	3.110	3.164	0.055
All Responses	704	3.764	3.638	-0.126

4.250 to 4.022
4.021 to 3.794
3.793 to 3.566
3.565 to 3.338
3.337 to 3.110

The Gaps reflect the difference between the average score for the importance of the strategy and the average score for the frequency with which fluid power is used in that strategy. When considering which strategies to focus on, factors like higher importance and large negative gaps should be taken into account.

Based on this analysis, the Task Force agreed that the following strategies may comprise the highest priorities for the 2025 Industrial Technology Roadmap:

- Safety
- Precision Control
- Automation
- Maintenance and Support
- Connectivity
- Electric Actuation

CAPABILITY IMPROVEMENTS

Capability Improvements describe the ways in which fluid power systems must improve if they are to participate or increase their participation in the technology trends described by the Customer Strategies.

At its June 2025 meeting, the NFPA Industrial Technology Task Force reviewed the results of two April 2025 surveys conducted by NFPA to assess the usefulness of certain Capability Improvements in helping fluid power meet the Customer Strategies and to determine if any new Capability Improvements had emerged since the time of the 2023 NFPA Technology Roadmap. One survey asked about hydraulic capabilities; the other about pneumatic capabilities. Together, the surveys received responses from 119 individuals across the fluid power supply chain, including a large percentage from the NFPA Industrial Technology Task Force.

Based on the results of the 2023 NFPA Technology Roadmap and a subsequent discussion with the NFPA Industrial Technology Task Force, survey responders were asked to rate the importance of each of the following Capability Improvements for each of Customer Strategies associated with the Industrial Markets with which they were familiar.

Capability Improvements
In order to better meet the needs of our customers, fluid power should seek to:

- **Data.** Improve ability to monitor, gather, and use data generated from fluid power products and/or systems.
- **Control.** Improve the precision, performance, or ease the application of fluid power control systems.
- **Energy Efficiency.** Increase the energy efficiency of fluid power products and/or systems.
- **Environmental Impact.** Reduce the environmental impact of fluid power products and/or systems (i.e., leaks, sustainable materials, damage to environment).
- **Noise.** Reduce the level and harshness of the noise generated by fluid power products and/or systems.
- **Power Density.** Increase the power density of fluid power products and/or systems.
- **Reliability and Durability.** Improve the reliability and/or durability of fluid power products and/or systems.
- **Safety.** Improve the safe use and application of fluid power products and/or systems.
- **Service.** Improve the availability of replacement parts or otherwise improve the servicing of the fluid power system on the machine.

<u>Importance of Existing Capability Improvements</u>

Survey participants were asked to rate how important each of the Capability Improvements would be in increasing the use of **Hydraulics** for each of Customer Strategies associated with the Industrial

Markets with which they were familiar. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

		HYDRAULIC CAPABILITY IMPROVEMENTS								
CUSTOMER STRATEGIES	N	Data	Control	Energy Efficiency	Environmental Impact	Noise	Power Denisty	Reliability and Durability	Safety	Service
Automation	74	3.622	4.243	3.932	3.284	3.446	3.500	4.257	4.135	3.824
Compactness	69	3.319	3.884	3.826	3.246	3.420	3.841	3.913	3.841	3.696
Connectivity	67	3.985	3.866	3.582	3.134	3.045	3.030	3.970	3.746	3.582
Electric Actuation	62	3.984	4.081	3.871	3.323	3.500	3.677	4.000	3.774	3.661
Energy Efficiency	63	3.651	3.841	4.175	3.302	3.429	3.714	3.968	3.730	3.667
Environmental Impact	62	3.371	3.339	3.565	3.774	3.274	3.306	3.516	3.452	3.323
Maintenance and Support	62	3.694	3.790	3.371	3.032	3.323	3.258	4.323	3.774	4.242
Precision Control	62	3.839	4.403	3.661	3.016	3.323	3.468	3.984	3.855	3.581
Safety	61	3.803	3.934	3.230	3.098	3.492	3.098	3.918	4.459	3.656
All Responses	582	3.692	3.936	3.698	3.246	3.361	3.436	3.988	3.866	3.694

4.459 to 4.170
4.169 to 3.882
3.881 to 3.593
3.592 to 3.305
3.304 to 3.016

In the aggregate, 100% of the improvement choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

Survey participants were then asked to rate how important each of the Capability Improvements would be in increasing the use of **Pneumatics** for each of Customer Strategies associated with the Industrial Markets with which they were familiar. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

		PNEUMATIC CAPABILITY IMPROVEMENTS								
CUSTOMER STRATEGIES	N	Data	Control	Energy Efficiency	Environmental Impact	Noise	Power Denisty	Reliability and Durability	Safety	Service
Automation	20	3.550	3.800	3.350	3.200	3.300	3.200	4.400	4.200	4.050
Compactness	18	3.500	3.611	3.611	3.222	3.222	3.500	4.111	4.056	4.000
Connectivity	14	3.929	3.929	3.143	2.857	3.214	3.214	4.071	4.000	3.643
Electric Actuation	13	3.692	4.077	3.615	3.000	2.692	3.077	4.154	4.000	3.538
Energy Efficiency	12	3.500	3.833	3.833	3.833	3.250	3.750	3.667	3.833	3.417
Environmental Impact	12	3.250	3.417	3.750	3.500	3.083	3.333	3.833	3.750	3.333
Maintenance and Support	12	3.667	3.417	3.083	3.000	3.167	3.000	4.083	4.000	4.000
Precision Control	12	3.500	4.250	3.167	2.833	3.000	3.333	3.917	4.083	3.417
Safety	12	3.333	3.500	2.917	2.750	3.250	2.833	4.000	4.250	3.333
All Responses	125	3.552	3.760	3.392	3.136	3.144	3.256	4.056	4.032	3.680

4.400 to 4.058
4.057 to 3.717
3.716 to 3.375
3.374 to 3.034
3.033 to 2.692

In the aggregate, 93% of the improvement choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

When we aggregate the hydraulic and pneumatic responses and order the chart from most to least important Capability Improvement, we see the results shown below.

CUSTOMER STRATEGIES	N	FLUID POWER CAPABILITY IMPROVEMENTS								
		Reliability and Durability	Control	Safety	Service	Data	Energy Efficiency	Power Denisty	Noise	Environmental Impact
Automation	94	4.287	4.149	4.149	3.872	3.606	3.809	3.436	3.415	3.266
Compactness	87	3.954	3.828	3.885	3.759	3.356	3.782	3.770	3.379	3.241
Connectivity	81	3.988	3.877	3.790	3.593	3.975	3.506	3.062	3.074	3.086
Electric Actuation	75	4.027	4.080	3.813	3.640	3.933	3.827	3.573	3.360	3.267
Energy Efficiency	75	3.920	3.840	3.747	3.627	3.627	4.120	3.720	3.400	3.387
Environmental Impact	74	3.568	3.351	3.500	3.324	3.351	3.595	3.311	3.243	3.730
Maintenance and Support	74	4.284	3.730	3.811	4.203	3.689	3.324	3.216	3.297	3.027
Precision Control	74	3.973	4.378	3.892	3.554	3.784	3.581	3.446	3.270	2.986
Safety	73	3.932	3.863	4.425	3.603	3.726	3.178	3.055	3.452	3.041
All Responses	707	4.000	3.905	3.895	3.692	3.668	3.644	3.405	3.322	3.226

4.425 to 4.137
4.136 to 3.849
3.848 to 3.562
3.561 to 3.274
3.273 to 2.986

In the aggregate, 99% of the improvement choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

Identification of Capability Improvements for the 2025 Industrial Technology Roadmap

Several additional suggestions for Capability Improvements were made by the survey responders. Reviewing this quantitative and qualitative information at its June 2025 meeting, the NFPA Industrial Technology Task Force prioritized the following Capability Improvements for the 2025 Industrial Technology Roadmap.

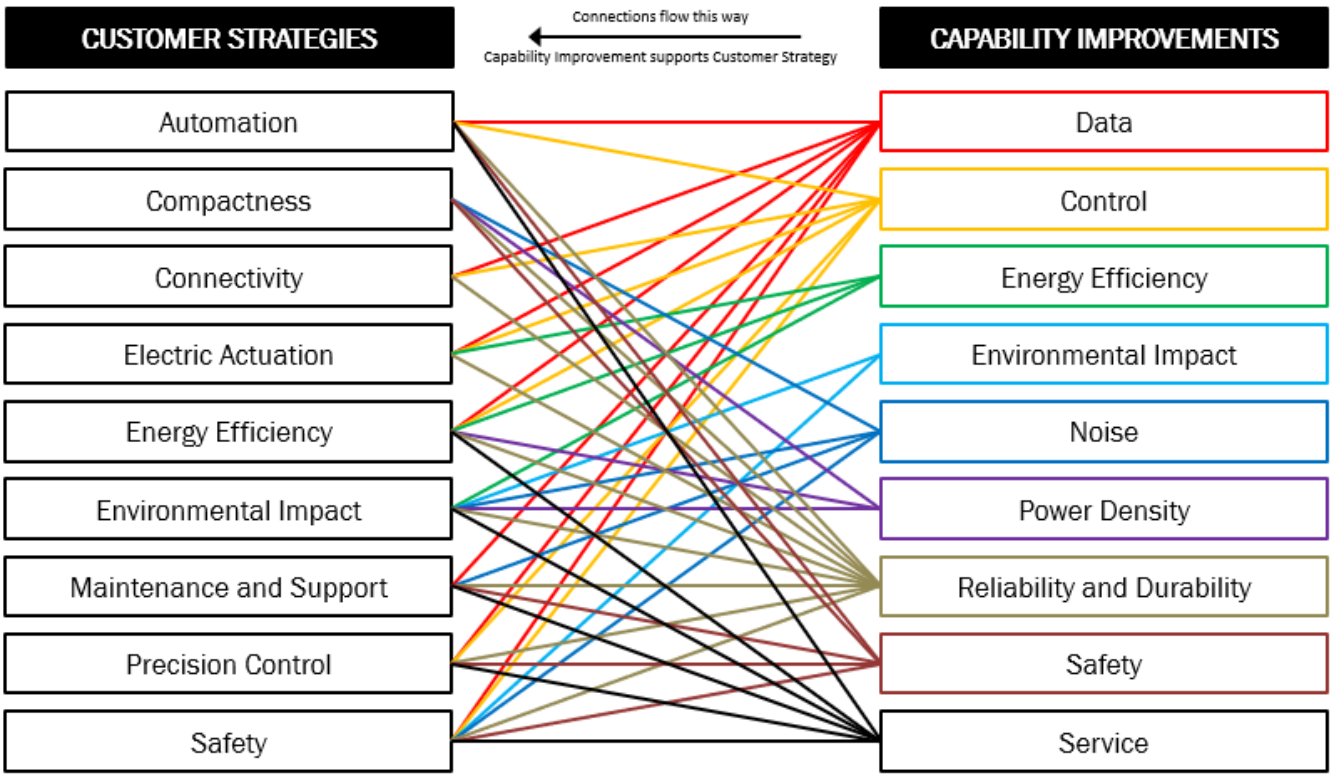
Capability Improvements

In order to better meet the needs of our customers, fluid power should seek to:

- **Data.** Improve ability to monitor, gather, and use data generated from fluid power products and/or systems.
- **Control.** Improve the precision, performance, or ease the application of fluid power control systems.
- **Energy Efficiency.** Increase the energy efficiency of fluid power products and/or systems.
- **Environmental Impact.** Reduce the environmental impact of fluid power products and/or systems (i.e., leaks, sustainable materials, damage to environment).
- **Noise.** Reduce the level and harshness of the noise generated by fluid power products and/or systems.
- **Power Density.** Increase the power density of fluid power products and/or systems.
- **Reliability and Durability.** Improve the reliability and/or durability of fluid power products and/or systems.
- **Safety.** Improve the safe use and application of fluid power products and/or systems.
- **Service.** Improve the availability of replacement parts or otherwise improve the servicing of the fluid power system on the machine.

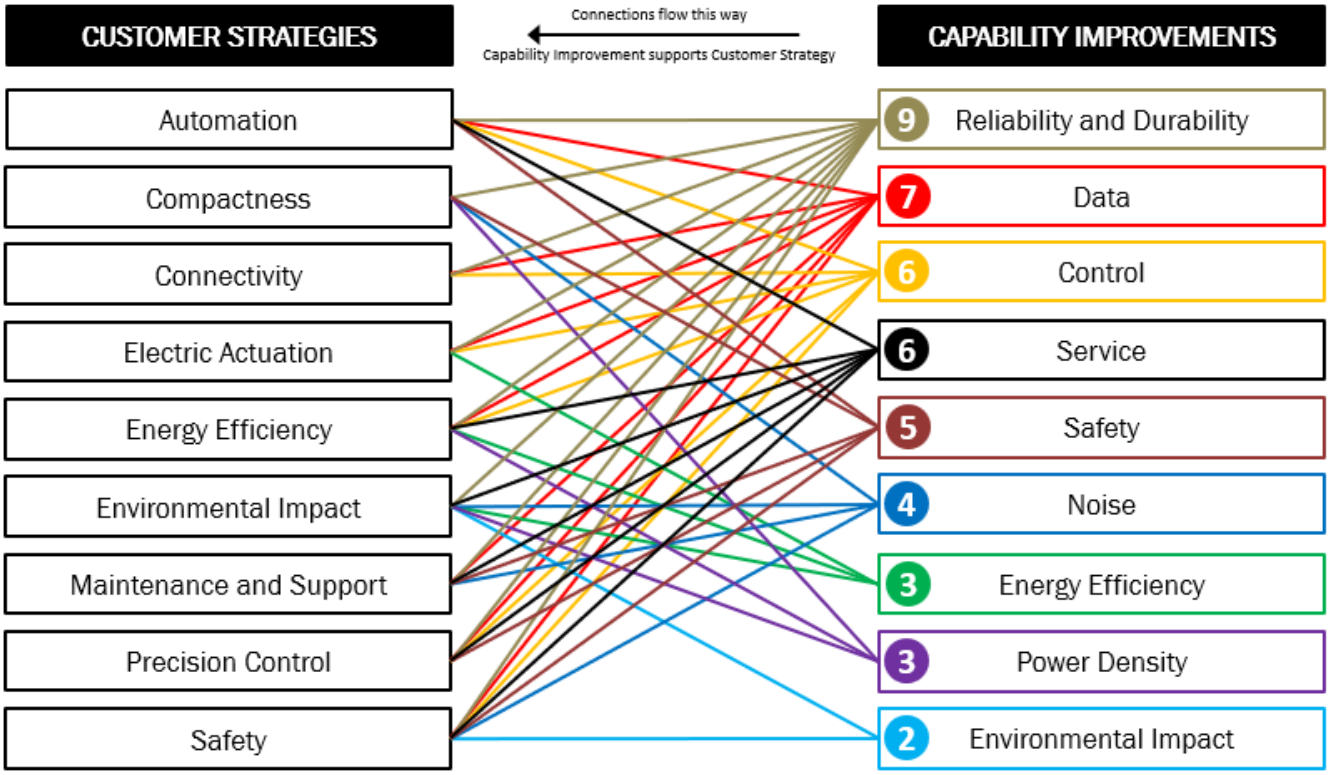
Connections to Customer Strategies

The Task Force discussed possible connections between the prioritized Capability Improvements and Customer Strategies, recognizing that each improvement could be used to help the machine builder achieve multiple strategies. A map of these connections is shown below:



Prioritizing the Capability Improvements by the number of Customer Strategies they could impact results in the following connection map:

IMPROVING FLUID POWER COMPONENTS AND SYSTEMS FOR INDUSTRIAL APPLICATIONS



DEFINITION OF PRE-COMPETITIVE RESEARCH

Pre-competitive research is performed at the time in the technology development cycle when interested, but potentially competitive parties agree that there is value to be gained from a collaborative rather than a competitive approach.

It generally resides in the middle ground between fundamental basic research conducted mainly in universities and proprietary research performed or directed mainly by companies. It can be performed to develop new technologies or to determine the market readiness of new technologies.

For the purposes of developing the Research Areas and Targets included in this report, members of the NFPA Industrial Technology Task Force focused on pre-competitive activities and recommendations.

RESEARCH AREAS

Research Areas are the broad areas of pre-competitive investigation that could assist in bringing about the Capability Improvements.

At its September 2025 meeting, the NFPA Industrial Technology Task Force reviewed the results of two July 2025 surveys conducted by NFPA to assess the usefulness of certain Research Areas in bringing about the improvements described by the Capability Improvements and to determine if any new Research Areas had emerged since the time of the 2023 NFPA Technology Roadmap. One survey asked about hydraulic research areas; the other about pneumatic research areas. Together, the surveys received responses from 61 individuals across the fluid power supply chain, including a large percentage from the NFPA Industrial Technology Task Force.

Based on the results of the 2023 NFPA Technology Roadmap and a subsequent discussion with the NFPA Industrial Technology Task Force, survey responders were asked to rate the importance of each of the following Research Areas for each of Capability Improvements.

Research Areas
Organizations that wish to pursue research of importance to the fluid power industry should focus on projects that:

- **Components.** Develop new fluid power components.
- **Controllability.** Improve the controllability of fluid power systems.
- **Data Analytics.** Improve use of data analytics in fluid power systems.
- **Fluids.** Optimize the use of fluids and lubrication in fluid power systems.
- **Manufacturing Technologies.** Develop/apply new manufacturing technologies for fluid power components and systems.
- **Materials.** Develop/apply new materials in fluid power components and systems.
- **Seal Technologies.** Optimize the use of seal technologies in fluid power systems.
- **Security.** Improve data, cyber or other security needs of fluid power systems.
- **Sensor Technologies.** Advance sensor technologies used in fluid power systems.
- **System Architectures.** Explore novel fluid power system architectures.

<u>Importance of Existing Research Areas</u>

Survey participants were asked to rate how important each of the Research Areas would be in making a significant impact on each of the Capability Improvements for **Hydraulics**. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

CAPABILITY IMPROVEMENTS	N	HYDRAULIC RESEARCH AREAS									
		Components	Controllability	Data Analytics	Fluids	Manufacturing Technologies	Materials	Seal Technologies	Security	Sensor Technologies	System Architectures
Data	38	3.711	4.000	4.000	3.316	3.605	3.263	3.211	3.342	3.974	3.368
Control	34	3.735	4.176	3.882	3.147	3.324	3.265	3.529	3.206	4.029	3.706
Energy Efficiency	32	3.969	4.063	3.844	3.469	3.250	3.375	3.625	2.625	3.875	3.969
Environmental Impact	32	3.594	3.469	2.938	3.719	3.656	3.531	3.906	2.281	3.219	3.594
Noise	32	3.969	3.656	3.125	3.469	3.219	3.438	3.125	2.281	3.313	3.938
Power Density	32	4.156	3.531	3.156	3.500	3.313	4.156	3.688	2.156	3.781	4.125
Reliability and Durability	32	4.000	3.688	3.594	3.719	3.531	3.938	4.000	2.531	3.844	3.875
Safety	32	3.438	3.969	3.500	3.063	3.063	3.406	3.688	3.344	3.969	3.594
Service	33	3.303	2.909	3.424	3.091	3.394	3.273	3.364	2.545	3.182	3.212
All Responses	297	3.761	3.724	3.508	3.384	3.377	3.508	3.562	2.717	3.694	3.700

4.176 to 3.773
3.772 to 3.369
3.368 to 2.965
2.964 to 2.561
2.560 to 2.156

In the aggregate, 91% of the research area choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

Survey participants were also asked to rate how important each of the Research Areas would be in making a significant impact on each of the Capability Improvements for **Pneumatics**. The scoring scale was: 5 = Extremely important; 4 = Very important; 3 = Somewhat important; 2 = Not so important; 1 = Not at all important.

CAPABILITY IMPROVEMENTS	N	PNEUMATIC RESEARCH AREAS									
		Components	Controllability	Data Analytics	Fluids	Manufacturing Technologies	Materials	Seal Technologies	Security	Sensor Technologies	System Architectures
Data	9	3.333	3.889	3.778	2.222	3.444	2.444	2.667	2.889	4.111	3.333
Control	8	3.875	3.625	3.375	2.875	3.500	2.875	2.875	2.750	3.750	3.500
Energy Efficiency	8	3.625	3.750	3.750	3.000	3.000	3.250	3.750	2.375	4.125	3.625
Environmental Impact	7	3.857	4.000	3.429	3.429	3.286	4.143	3.571	2.286	3.857	3.857
Noise	7	3.571	3.286	2.714	3.143	2.857	3.429	3.143	2.000	2.857	3.429
Power Density	7	3.714	3.857	2.571	3.429	3.429	4.000	3.714	1.857	3.000	4.000
Reliability and Durability	7	4.143	3.714	3.143	3.571	3.857	4.143	3.571	1.857	3.571	3.286
Safety	7	3.429	4.143	3.286	2.857	2.429	3.143	2.714	2.571	3.857	3.857
Service	7	3.429	2.714	3.714	2.429	3.286	3.571	2.429	2.286	3.714	2.857
All Responses	67	3.657	3.672	3.328	2.970	3.239	3.403	3.149	2.343	3.672	3.522

4.143 to 3.686
3.685 to 3.229
3.228 to 2.771
2.770 to 2.314
2.313 to 1.857

In the aggregate, only 71% of the research area choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

When we aggregate the hydraulic and pneumatic responses and order the chart from most to least important Research Area, we see the results shown below.

CAPABILITY IMPROVEMENTS	N	FLUID POWER RESEARCH AREAS									
		Components	Controllability	Sensor Technologies	System Architectures	Materials	Seal Technologies	Data Analytics	Manufacturing Technologies	Fluids	Security
Data	47	3.638	3.979	4.000	3.362	3.106	3.106	3.957	3.574	3.106	3.255
Control	42	3.762	4.071	3.976	3.667	3.190	3.405	3.786	3.357	3.095	3.119
Energy Efficiency	40	3.900	4.000	3.925	3.900	3.350	3.650	3.825	3.200	3.375	2.575
Environmental Impact	39	3.641	3.564	3.333	3.641	3.641	3.846	3.026	3.590	3.667	2.282
Noise	39	3.897	3.590	3.231	3.846	3.436	3.128	3.051	3.154	3.410	2.231
Power Density	39	4.077	3.590	3.641	4.103	4.128	3.692	3.051	3.333	3.487	2.103
Reliability and Durability	39	4.026	3.692	3.795	3.769	3.974	3.923	3.513	3.590	3.692	2.410
Safety	39	3.436	4.000	3.949	3.641	3.359	3.513	3.462	2.949	3.026	3.205
Service	40	3.325	2.875	3.275	3.150	3.325	3.200	3.475	3.375	2.975	2.500
All Responses	364	3.742	3.714	3.690	3.668	3.489	3.486	3.475	3.352	3.308	2.648

4.128 to 3.724
3.723 to 3.319
3.318 to 2.914
2.913 to 2.509
2.508 to 2.103

In the aggregate, 90% of the research area choices were rated as at least somewhat important. The color codes categorize the average scores into their quintiles – with dark green and light green representing averages in the upper 40% of the response range.

Identification of Research Areas for the 2025 Industrial Technology Roadmap

Several additional suggestions for Research Areas were made by the survey responders. This quantitative and qualitative information was reviewed by a series of Working Groups, one for each of the prioritized Capability Improvements, at a series of meetings in August 2025. The Working Groups returned a set of prioritized Research Areas, which were adopted by the NFPA Industrial Technology Task Force at its September 2025 meeting for the 2025 Industrial Technology Roadmap.

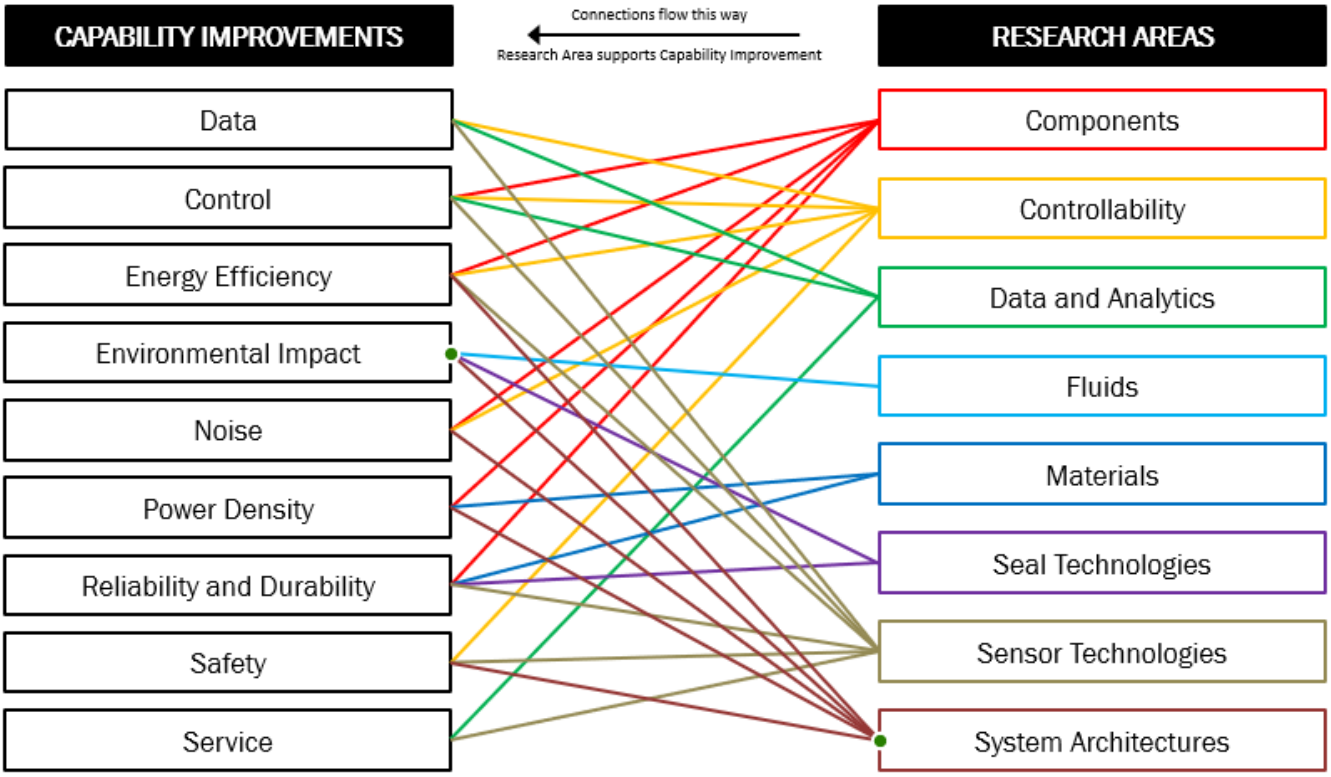
Research Areas

Organizations that wish to pursue research of importance to the fluid power industry should focus on projects that:

- **Components.** Develop new fluid power components.
- **Controllability.** Improve the controllability of fluid power systems.
- **Data and Analytics.** Improve the gathering and use of data analytics in fluid power systems.
- **Fluids.** Optimize the use of fluids and lubrication in fluid power systems.
- **Materials.** Develop/apply new materials in fluid power components and systems.
- **Seal Technologies.** Optimize the use of seal technologies in fluid power systems.
- **Sensor Technologies.** Advance sensor technologies used in fluid power systems.
- **System Architectures.** Explore novel fluid power system architectures.

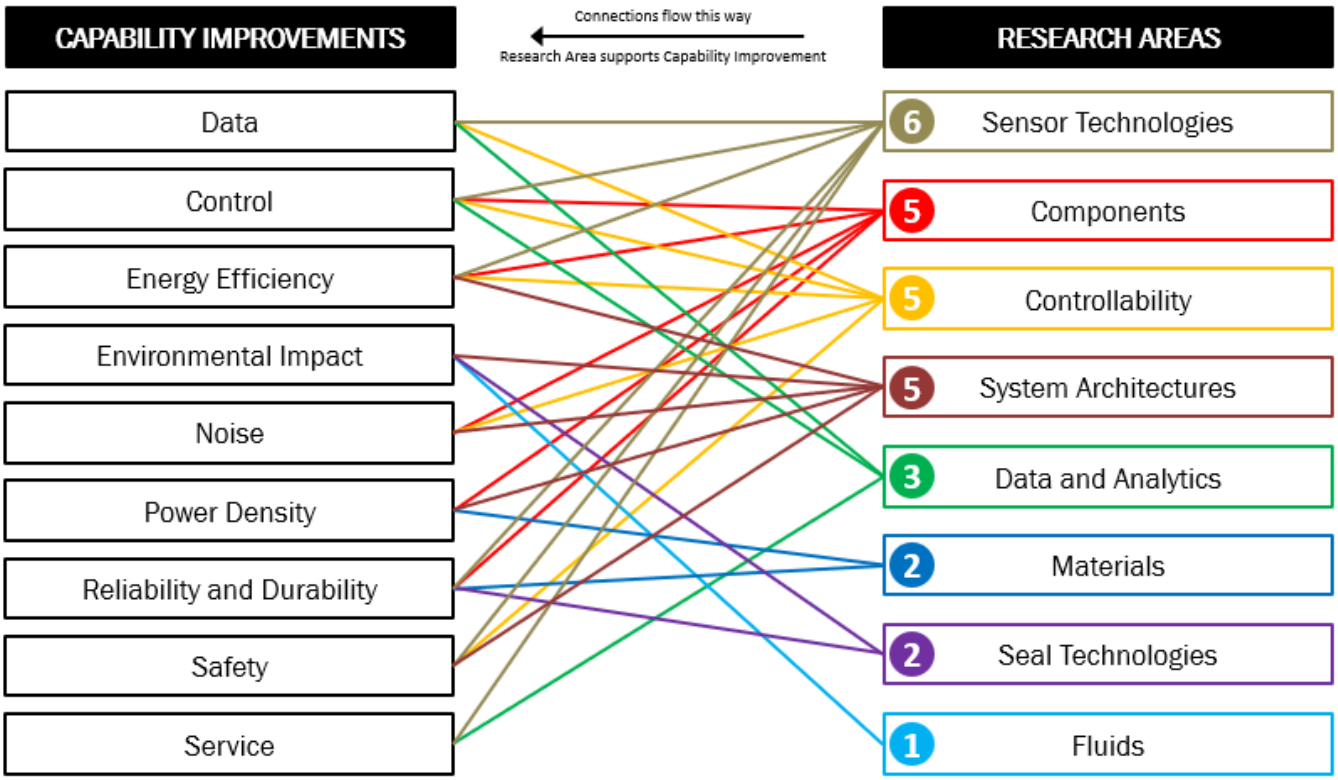
Connections to Capability Improvements

The Working Groups and Task Force discussed possible connections between the prioritized Research Areas and Capability Improvements, recognizing that each area could be used to help achieve multiple improvements. A map of these connections is shown below:



Prioritizing the Research Areas by the number of Capability Improvements they could impact results in the following connection map:

IMPROVING FLUID POWER COMPONENTS AND SYSTEMS FOR INDUSTRIAL APPLICATIONS



RESEARCH TARGETS FOR EACH CAPABILITY IMPROVEMENT

Research Targets are the objectives that quantify or otherwise describe successful strategies for pursuing the Research Areas.

Following the identification of the final Capability Improvements for the 2025 NFPA Industrial Technology Roadmap, the NFPA Industrial Technology Task Force established nine Working Groups, one for each Capability Improvement, and tasked each with identifying a prioritized list of pre-competitive Research Areas and Targets that could best assist in bringing about its Capability Improvement.

These Working Groups met in August 2025. In addition to selecting the Research Areas prioritized for their Capability Improvement, each Group developed the following list of Research Targets, designed to provide additional guidance for organizations that wish to pursue research, market education, or standardization projects of importance to the fluid power industry.

I. DATA. Improve ability to monitor, gather, and use data generated from fluid power products and/or systems.

A. Controllability. Improve the controllability of fluid power systems.
1. Simplify the application of advanced control architectures.
2. Increase the use of wireless sensors for data collection and reliable remote control of systems.
3. Explore the use of digital twins and related simulation technologies to test and validate improved control of fluid power components.

B. Data and Analytics. Improve the gathering and use of data analytics in fluid power systems.
1. Ensure compliance with industry standard communication protocols.
2. Ensure compliance with data protection regulations (CA, Europe, etc.)
3. Increase the standardization of data formats across systems and components.
4. Explore the use of AI (artificial intelligence) to predict and make decisions for improving system performance.

C. Sensor Technologies. Advance sensor technologies used in fluid power systems.
1. Increase the durability and survivability of sensors in harsh environments.
2. Develop sensors that can be more easily applied across the system (i.e., miniaturization, integration of functions - multiple measurements from the same sensor in the same location).
3. Explore “non-traditional” or “new-to-fluid-power” sensor modalities for possible application to fluid power objectives (i.e., vibration sensors for maintenance and fault detection).

II. CONTROL. Improve the precision, performance, or ease the application of fluid power control systems.

A. Components. Develop new fluid power components.
1. Increase the integration of sensors into components.
2. Integrate more components into the machine network.
3. Investigate the potential for new and needed functions for fluid power components (especially those that address common pain points on the machine).

B. Controllability. Improve the controllability of fluid power systems.
1. Review emerging safety requirements (i.e., European, Asian) and educate the marketplace with specific future timeline of impacts on the North American market of fluid power control systems.
2. Increase the application of advanced concepts for fluid power control (i.e., closed loop control, position sensing).
3. Increase translation of "academic" control strategies to real-world application (i.e., robust control, adaptive control).

C. Data and Analytics. Improve the gathering and use of data analytics in fluid power systems.
1. Define and describe effective data analysis strategies that improve the control of fluid power systems (i.e., monitoring and refining cyclical processes), especially in ways that compare favorably to the control of electromechanical systems.
2. Analyze electromechanical control systems and adopt/educate on similar strategies for fluid power systems (i.e., for improved precision and accuracy).

D. Sensor Technologies. Advance sensor technologies used in fluid power systems.
1. Perform cost-benefit analysis of increased use of sensors and the performance enhancements that they can provide.
2. Investigate the potential use of advanced sensors from other industries in fluid power systems (i.e., automotive, aerospace).
3. Define and specify existing sensors needed for advanced control strategies (i.e., robust control, adaptive control).

III. ENERGY EFFICIENCY. Increase the energy efficiency of fluid power products and/or systems.

A. Components. Develop new fluid power components.
1. Find ways to improve the efficiency of individual components (i.e., reducing losses, improving energy conversion, reducing coil wattage in control systems).

B. Controllability. Improve the controllability of fluid power systems.
1. Improve the ability of control to reduce losses in the fluid power system (i.e., utilizing sensors to minimize the pressure and flow required to perform needed work).

2. Develop accurate model-based simulations for control systems and components (i.e., digital twins, improvements in the characterization of components to accomplish this).

C. Sensor Technologies. Advance sensor technologies used in fluid power systems.
1. Increase use and availability of multi-functional wireless sensors to measure pressure, temperature, and flow (i.e., reduce cost, cybersecurity concerns).
2. Increase the precision and response time of sensors.
3. Increase the uniform connectivity of sensors.

D. System Architectures. Explore novel fluid power system architectures.
1. Utilize active displacement control to use only the fluid flow needed.
2. Utilize distributed subsystems to customize pressure and flow to individual work circuits.
3. Develop methods to recover energy from the system and use it for additional work.

IV. ENVIRONMENTAL IMPACT. Reduce the environmental impact of fluid power products and/or systems (i.e., leaks, sustainable materials, damage to environment).

A. Fluids. Optimize the use of fluids and lubrication in fluid power systems.
1. Develop biodegradable fluids that have lower cost, greater lubricity, greater seal compatibility, and can operate at a wider temperature range.

B. Seal Technologies. Optimize the use of seal technologies in fluid power systems.
1. Define, assess current use of, and educate market on best practices (including surface finishes, side loading, external temperature) for seal and connection types.

C. System Architectures. Explore novel fluid power system architectures.
1. Produce a system design guide that focuses on strategies that can reduce environmental impact (i.e., reduce the number of connections, shape and configuration of fluid conduits, integration of components, properly regulate pressure, reduce the volume of fluid, thermal conditioning of fluid, properly size the system to the application).

V. NOISE. Reduce the level and harshness of the noise generated by fluid power products and/or systems.

A. Components. Develop new fluid power components.
1. Design considerations for lower noise into components (i.e., expand flow paths within manifolds, incorporation of noise-dampening materials).
2. Define and promote acceptable noise thresholds for components in specific industrial applications.

3. Explore 3D-printed component designs, appropriate for a production environment, that reduce noise levels.

B. Controllability. Improve the controllability of fluid power systems.

1. Define and promote best practices for control strategies that reduce the level and harshness of noise (i.e., dither adjustment, use of proportional valves, use of feedback to monitor case flow, spool position, optimizing hysteresis).
2. Increase use of sensors in fluid power systems to monitor and reduce vibration and noise levels (i.e., reducing cavitation and entrained air).

C. System Architectures. Explore novel fluid power system architectures.

1. Define and promote best practices for system architectures that reduce the level and harshness of noise (i.e., proper line sizing, flexible connections to prime movers, utilization of dampening materials, sizing components to energy needed).
2. Investigate the application of active noise cancellation technologies to fluid power systems.
3. Evaluate the external environment and implement strategies that reduce perceived levels of noise.

VI. POWER DENSITY. Increase the power density of fluid power products and/or systems.

Operating at higher pressure is the top-level objective. Research areas and targets reflect this. A independent study to determine current market pressures and the possibility for increases may be helpful.

A. Components. Develop new fluid power components.

1. Develop components that are smaller and can operate at higher pressure.
2. Develop more efficient components (i.e., less internal leakage).
3. Develop more durable components (i.e., longer service life).

B. Materials. Develop/apply new materials in fluid power components and systems.

1. Develop higher strength materials for fluid power components (including seals, hoses).
2. Optimize designs and materials used for additive manufacturing for higher pressure or smaller fluid power applications.

C. System Architectures. Explore novel fluid power system architectures.

1. Analyze and address the system development and safety needs associated with higher pressure (i.e., cost/benefit analysis, thermal management, new standards development).

VII. RELIABILITY AND DURABILITY. Improve the reliability and/or durability of fluid power products and/or systems.

A. Components. Develop new fluid power components.
1. Develop bearing-free components or utilize other alternatives to bearings.
2. Develop components that are more resistant to contamination (i.e., servo valves, manifolds).
3. Educate and accelerate evolution towards O-ring seals and away from tapered threads.
4. Increase use of on-board electronics to provide component data for better system integration.

B. Materials. Develop/apply new materials in fluid power components and systems.
1. Investigate the use of materials processing less prone to leaks (i.e., castings, 3D-printing, injection-molding).
2. Investigate the use of new materials (i.e., lead-free brass and steel, composites, PFAS-free).
3. Develop and apply coatings and heat-treat processes that increase resistance to wear-and-tear.

C. Seal Technologies. Optimize the use of seal technologies in fluid power systems.
1. Increase alignment between existing seal technologies and the application (materials, geometries, etc.).
2. Improve and increase use of predictive models for seal failures.
3. Develop seal technologies that are more resistant to cutting or scratching during assembly.

D. Sensor Technologies. Advance sensor technologies used in fluid power systems.
1. Apply sensor technologies to better predict product wear or failure (and make more cost-effective).
2. Apply in-line fluid sensors to monitor and act on contamination levels (and make more cost-effective).
3. Explore use of predictive algorithms to monitor and alert on component status.
4. Increase robustness of sensor connections (through proven and standard practices, etc.).

VIII. SAFETY. Improve the safe use and application of fluid power products and/or systems.

A. Controllability. Improve the controllability of fluid power systems.
1. Create and/or disseminate “handy reference guides” for handling of stored energy in ways that comply with ISO and ANSI standards.

2. Engage more fluid power experts in the efforts to update relevant standards for safe use of fluid power (i.e., ANSI B1126, ISO 4413,4414, ISO 14839).
3. Improve integration between machine controls and safety-related fluid power control systems.

B. Sensor Technologies. Advance sensor technologies used in fluid power systems.

1. Integrate more accurate position sensors into spool-position valves.
2. Clarify definition of reliable sensors and requirements for reliable use of sensors in safety systems.
3. Develop new or use existing sensors for spray or leak detection.
4. Increase robustness of industrial sensors for mobile or other harsh environments.
5. Investigate ways to integrate sensors into valves and other components.

C. System Architectures. Explore novel fluid power system architectures.

1. Educate the equipment OEM on safety standards and requirements to increase incorporation into system design.
2. Improve integration of less leak-prone fittings into hydraulic systems.
3. Develop new or improve existing technologies/architectures to safely relieve pressure in hydraulic systems.

IX. SERVICE. Improve the availability of replacement parts or otherwise improve the servicing of the fluid power system on the machine.

Technologies needed to perform preventative maintenance is the top-level objective. Research areas and targets reflect this.

A. Data and Analytics. Improve the gathering and use of data analytics in fluid power systems.

1. Quantify the impact of preventative maintenance strategies (i.e., performance, financial).
2. Provide guidance to system integrators on what sensors are needed, what they detect, and the service opportunities that they reveal (can be component-specific and dependent; can also be hydraulic or pneumatic-specific).

B. Sensor Technologies. Advance sensor technologies used in fluid power systems.

1. Develop new sensing technologies for flow and contamination that don't require disassembly of the machine.
2. Increase the integration of sensors into fluid power components (i.e., measurement ports).

PRIORITZED RESEARCH TARGETS FOR EACH RESEARCH AREA

Research Targets are the objectives that quantify or otherwise describe successful strategies for pursuing the Research Areas.

Following the Working Group meetings in August 2025, the NFPA Industrial Technology Task Force met in September 2025 to review the Research Targets that had been recommended by the each of the nine Working Groups and select those most likely to have the greatest impact on advancing each Research Area and, by extension, improving fluid power's capabilities and ability to address the needs described by the Customer Strategies.

COMPONENTS: Develop new fluid power components.

- Increase the integration of sensors into components.
- Investigate the potential for new and needed functions for fluid power components (especially those that address common pain points on the machine).
- Find ways to improve the efficiency of individual components (i.e., reducing losses, improving energy conversion, reducing coil wattage in control systems).

CONTROLLABILITY: Improve the controllability of fluid power systems.

- Simplify the application of advanced control architectures.
- Increase the use of wireless sensors for data collection and reliable remote control of systems.
- Develop accurate model-based simulations for control systems and components (i.e., digital twins, improvements in the characterization of components to accomplish this).
- Increase use of sensors in fluid power systems to monitor and reduce vibration and noise levels (i.e., reducing cavitation and entrained air).

DATA AND ANALYTICS: Improve the gathering and use of data analytics in fluid power systems.

- Ensure compliance with industry standard communication protocols.
- Ensure compliance with data protection regulations (CA, Europe, etc.)
- Explore the use of AI (artificial intelligence) to predict and make decisions for improving system performance.
- Provide guidance to system integrators on what sensors are needed, what they detect, and the service opportunities that they reveal (can be component-specific and dependent; can also be hydraulic or pneumatic-specific).

FLUIDS: Optimize the use of fluids and lubrication in fluid power systems.

- Develop biodegradable fluids that have lower cost, greater lubricity, greater seal compatibility, and can operate at a wider temperature range.

MATERIALS: Develop/apply new materials in fluid power components and systems.

- Investigate the use of new materials (i.e., lead-free brass and steel, composites, PFAS-free).

SEAL TECHNOLOGIES: Optimize the use of seal technologies in fluid power systems.

- Define, assess current use of, and educate market on best practices (including surface finishes, side loading, external temperature) for seal and connection types.
- Develop seal technologies that are more resistant to cutting or scratching during assembly.

SENSOR TECHNOLOGIES: Advance sensor technologies used in fluid power systems.

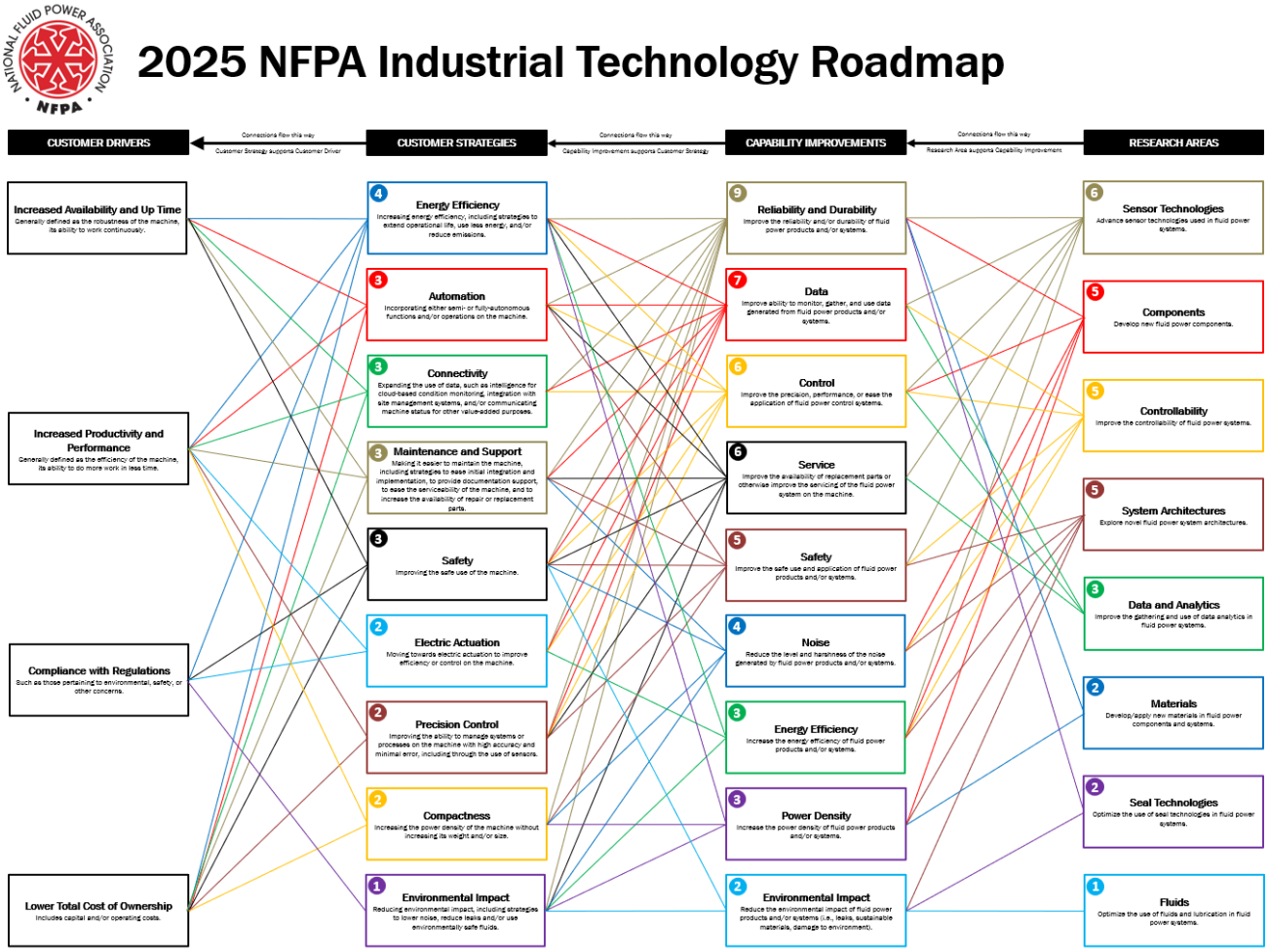
- Develop sensors that can be more easily applied across the system (i.e., miniaturization, integration of functions - multiple measurements from the same sensor in the same location).
- Increase use and availability of multi-functional wireless sensors to measure pressure, temperature, and flow (i.e., reduce cost, cybersecurity concerns).
- Explore use of predictive algorithms to monitor and alert on component status.

SYSTEM ARCHITECTURES: Explore novel fluid power system architectures.

- Utilize active displacement control to use only the fluid flow needed.
- Utilize distributed subsystems to customize pressure and flow to individual work circuits.
- Develop methods to recover energy from the system and use for additional work.

FULL TECHNOLOGY ROADMAP SCHEMATIC

A schematic of the full 2025 NFPA Industrial Technology Roadmap, showing all the connections between the Customer Drivers, Customer Strategies, Capability Improvements, and Research Areas, is shown below. A hi-res version of this schematic is available upon request from the NFPA office.



TASK FORCE AND WORKING GROUPS

The following individuals served on the NFPA Industrial Technology Task Force and participated in the various meetings and Working Groups it convened to help complete this report.

Participants at Task Force Meetings

Representative	Organization	12/2/24	3/14/25	6/9/25	9/8/25
Andy Curriston	ACE Controls	X	X		
Paul Johnson	Aggressive Hydraulics		X		X
Ada Leung	Anfield Industries				X
Kristopher Karbach	Boeing			X	
David Blanco	Bosch Rexroth			X	X
Jon Frey	Bosch Rexroth	X	X	X	X
Tom Shickel	Bosch Rexroth			X	X
Paul Keating	Certified Power Solutions				X
Vonn Bonnema	Continental Hydraulics				X
Gajendra Jagatap	Danfoss Power Solutions	X			X
Anantkumar Jain	Danfoss Power Solutions			X	
Tom Carlson	Deltrol Fluid Products	X	X	X	
Dale Dietel	DGD Fluid Power				X
Adam Livesay	Elevat	X	X		
Jonathan Gamble	Enfield Technologies	X	X	X	
Dave Coffee	EPCO Zero-Leak		X		
Denis Lenoble	Famic Technologies		X	X	X
Frank Latino	Festo	X		X	
Chris Passmore	Flodraulic Group	X			X
Jonathan Steigerwald	Gates	X			
Darshan Talagalage	GE Aerospace	X	X		
Chris Kolbe	HYDAC	X			X
Bernd Hunger	IC-Fluid Power	X	X	X	X
Josh Scarbrough	IFP Motion Solutions	X			
Brian Tritle	IFP Motion Solutions	X			
Jared Amundson	IMI	X			
Dave Tetzlaff	Innovative Hydraulics	X	X	X	X
Andy McMichael	JWF Technologies		X	X	
Mete Alpan	Kepner Products	X			
Greg Broschka	Kepner Products	X	X	X	
Michael Miles	KersTech		X		X
John Jennings	Lexair	X		X	X

Paul Michael	Milwaukee School of Engineering	X	X	X	X
Robert Forisch	Moog				X
Dave Geiger	Moog	X			
Chul Jang	Moog		X		
Bob Mosey	Mosey's Production Machinists		X		
John Corona	Nachi America	X			X
Mike Minard	Nass Controls			X	
Pete Alles	National Fluid Power Association	X	X	X	X
Ben Brown	National Fluid Power Association			X	X
Allison Forsythe	National Fluid Power Association	X	X		
Denise Husenica	National Fluid Power Association	X	X	X	X
Eric Lanke	National Fluid Power Association	X	X	X	X
Tom Florence	Nopak			X	
Tony Hennum	Nott Company	X			
T. J. Crenwick	OEM Controls				X
S. Brian Simons	OEM Controls		X		
Keith Simons	OEM Controls			X	
Ben Thomas	OEM Controls				X
Dan Worden	OEM Controls		X	X	X
Dan Mizell	Oilgear	X		X	
John Tudor	Oilgear			X	
Linda Caron	Parker Hannifin	X	X	X	
Keith Kushnir	Parker Hannifin		X	X	
Mark Schoessler	Parker Hannifin	X			
Chadwick Conte	Peninsular Cylinder	X		X	
Joshua Wilson	QCC	X		X	X
Jeffrey Borchers	ROSS Controls		X		X
Volker Schmitz	Schmalz			X	
Jon Jensen	SMC			X	X
Steve Meislahn	Sun Hydraulics			X	X
Andrew Newman	Sun Hydraulics		X		
Bryan Day	Thermal Transfer Products				X
Michael Magsam	Trelleborg Sealing Solutions	X		X	X
Katherine Quigley	Trelleborg Sealing Solutions	X	X		
Ethan Roth	Vermeer				X
Rick Guidish	VIS Hydraulics				X
Todd Daubenberger	White Cup Solutions			X	

<u>Working Group #1: Data</u>

- Tom Carlson, Deltrol Fluid Products

- Chadwick Conte, Peninsular Cylinder Company
- Robert Countiss, AKG of America
- Laszlo Dobo, Continental ContiTech
- Tony Hennum, Nott Company
- Gajendra Japatap, Danfoss Power Solutions
- Kristopher Karbach, Boeing
- Eric Lanke, NFPA
- Frank Latino, Festo
- Steven Meislahn, Sun Hydraulics
- Paul Michael, Milwaukee School of Engineering
- Mike Minard, Nass Controls
- Andrew Newman, Sun Hydraulics
- Josh Scarbrough, IFP Motion Solutions
- Sam Simons, OEM Controls

Working Group #2: Control

- Chandlar Armstrong, IFP Motion Solutions
- Tom Carlson, Deltrol Fluid Products
- T.J. Crenwick, OEM Controls
- Jonathan Gamble, Enfield Technologies
- Sean Howley, Bailey International
- Jeff Keating, Certified Power Solutions
- Eric Lanke, NFPA
- Daniel Lavelle, Bosch Rexroth
- Andrew Newman, Sun Hydraulics
- Keith Simons, OEM Controls
- Josh Wilson, QCC

Working Group #3: Energy Efficiency

- Anant Jain, Danfoss Power Solutions
- Jon Jensen, SMC
- Eric Lanke, NFPA
- Steve Meislahn, Sun Hydraulics
- Michael Miles, KersTech
- Jared Ottman, Pettibone
- Mark Petit, Evonik Oil Additives
- Brian Rhode, Afton Chemical

Working Group #4: Environmental Impact

- Francesca Aryee-Dematteis, IMI

- David Coffee, EPCO Zero-Leak
- Matt Grussing, Bailey International
- Christopher Kolbe, HYDAC
- Eric Lanke, NFPA
- Andy McMichael, JWF Technologies

Working Group #5: Noise

- Narendra Gupta, Hyster-Yale Group
- Eric Lanke, NFPA
- Andy McMichael, JWF Technologies
- Mark Schoessler, Parker Hannifin
- Tom Shickel, Bosch Rexroth

Working Group #6: Power Density

- David Blanco, Bosch Rexroth
- Greg Broschka, Kepner Products
- Eric Lanke, NFPA
- Mark Schoessler, Parker Hannifin
- Josh Wilson, QCC

Working Group #7: Reliability and Durability

- Jeffrey Borchers, ROSS Controls
- Greg Broschka, Kepner Products Company
- Bernd Hunger, IC-Fluid Power
- Keith Kushnir, Parker Hannifin
- Eric Lanke, NFPA
- Denis Lenoble, Famic Technologies
- Bob Mosey, Mosey's Production Machinists
- Tim O'Neill, Kuriyama of America
- Jared Ottman, Pettibone
- Brian Rhode, Afton Chemical
- Ben Thomas, OEM Controls
- Josh Wilson, QCC

Working Group #8: Safety

- Jon Jensen, SMC
- Eric Lanke, NFPA
- Tim O'Neill, Kuriyama of America
- Jared Ottman, Pettibone
- Aaron Woynaroski, ROSS Controls

Working Group #9: Service

- Steve Downey, Hydraulex Global
- John Jennings, Lexair
- Eric Lanke, NFPA
- Josh Wilson, QCC