— BUREAU OF —
RECLAMATION

Final Report No. ST-2025-20100-01

Alternative Fire Suppression Systems for Hydroelectric Generators– Research and Analysis

Research and Development Office

Science and Technology

Research Program

August 2025

U.S. Department of the Interior

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE (DD-MM-YYYY) August 5, 2025	2. REPORT TYPE Research	3. DATES COVERED *(From - To)* 2019 - 2025

4. TITLE AND SUBTITLE

Alternative Fire Suppression Systems for Hydroelectric Generators– Research and Analysis

5a. CONTRACT NUMBER

F279A/ Y0100

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

1541 (S&T)

6. AUTHOR(S)

Sean Kyer F.P.E, Mechanical Engineer

Randy Egan P.E, Mechanical Engineer

5d. PROJECT ID NUMBER

Final Report ST-2025-20100

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Technical Service Center (TSC)
Denver Federal Center
PO Box 25007, Denver, CO 80225-0007

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Science and Technology Program
Research and Development Office
Bureau of Reclamation
U.S. Department of the Interior
Denver Federal Center
PO Box 25007, Denver, CO 80225-0007

10. SPONSOR/MONITOR'S ACRONYM(S)

Reclamation

11. SPONSOR/MONITOR'S REPORT NUMBER

Report Number 01

12. DISTRIBUTION/AVAILABILITY STATEMENT

Final Report may be downloaded from https://www.usbr.gov/research/projects/index.html

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This study reviews alternatives to carbon dioxide (CO_2) fire suppression systems used in Bureau of Reclamation hydroelectric generators. CO_2 systems, though effective, present severe life-safety hazards, face obsolescence, and require intensive maintenance. The research evaluates water-based, water mist, clean agent, inert gas, hybrid, and chemical systems against effectiveness, safety, reliability, maintainability, cost, and environmental impact.

Key Points

- CO_2 systems are effective but increasingly unsafe and unsustainable.
- Water mist and inert gas systems provide strong performance with improved life safety.
- Hybrid water mist/inert gas systems show the highest overall potential.
- Clean agents face environmental and regulatory challenges.
- Dry/wet chemical systems are unsuitable for generators.

Conclusions

While CO_2 has protected generators for decades, its safety risks outweigh its benefits. Hybrid, inert gas, and water mist systems offer the most balanced alternatives, combining reliable suppression with enhanced personnel protection. Transitioning to these technologies will reduce operational risk, improve safety, and ensure long-term resilience of Reclamation’s power infrastructure.

15. SUBJECT TERMS

Carbon dioxide extinguishing systems, alternative systems, hybrid fire extinguishing systems

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON Sean Kyer
a. REPORT U	b. ABSTRACT U	c. THIS PAGE U			19b. TELEPHONE NUMBER *(Include area code)* 303-445-2294

Mission Statements

Disclaimer

Acknowledgements

The Science and Technology Program, Bureau of Reclamation, sponsored this research.

Cover Image – A typical high-pressure carbon dioxide suppression system with a single bank of carbon dioxide cylinders, old mechanical counterweight routing valves, and explosive squib activation. (Egan/Bureau of Reclamation).

Alternative Fire Suppression Systems for Hydroelectric Generators– Research and Analysis

Final Report No. ST-2025-20100-01

Prepared by:

Technical Service Center

Sean Kyer F.P.E, Mechanical Engineer

Randy Egan P.E, Mechanical Engineer

Peer Review

Bureau of Reclamation
Research and Development Office
Science and Technology
Research Program

Final Report No. ST-2025-20100-01

Alternative Fire Suppression Systems for Hydroelectric Generators– Research and Analysis

SEAN KYER Digitally signed by SEAN KYER
Date: 2026.03.17 17:30:30 -06'00'

Prepared by: Sean Kyer F.P.E.

Mechanical Engineer, Mechanical Structures 86-68420

Peer review by: Meghan E. DiUbaldo, P.E.

Manager, Mechanical Piping & Systems 86-68410

This document has been reviewed under the Research and Development Office Discretionary peer review process, consistent with Reclamation Policy CMP P14. It does not represent and should not be construed to represent the Bureau of Reclamation's determination, concurrence, or policy.

Acronyms and Abbreviations

Ar	Argon
CO_2	Carbon dioxide
DOI	U.S. Department of the Interior
EPA	U.S. Environmental Protection Agency
FIST	Facilities Instructions, Standards, and Techniques
FMEA	Failure mode and effects ananlysis
hybrid	Hybrid fire extinguishing systems
ITM	Installation, testing, and maintenance
LOAEL	Lowest observed adverse effect level
LOTO	Lockout/Tagout
N_2	Nitrogen
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
N/A	not available; not applicable
NOAEL	No observed adverse effect level
O_2	Oxygen
PFAS	Polyfluoroalkyl substances
RBD	Reliability block diagrram
S&T	Science and Technology
SCBA	Self-contained breathing apparatus
Reclamation	Bureau of Reclamation
TSC	Technical Service Center

Symbols

≈	approximately equal to
BTU	british thermal unit
Δ	change in
c	centimeter
©	copyright
°C	Celsius
=	equal to
°F	Fahrenheit
ft	feet/foot
>	greater than
≥	greater than or equal to

kJ	kilo-Jule
<	less than
$\leq$	less than or equal to
m^3	meters cubed
µg/L	microgram per liter
ppm	parts per million
psi	pounds per square inch
%	percent
^	to the power of

Contents

Page

Executive Summary 1

1.0 Introduction 1

- 1.1. Study Overview 1
  - 1.1.1. Key Topics Covered: 1
  - 1.1.2. Goals 2

2.0 Background 2

- 2.1. Reclamation CO_2 systems. 2
- 2.2. Aging CO_2 Systems and Reclamation's Urgency for Action 4
- 2.3. CO_2 Fire Suppression – Hazards, Safety Measures, and the Case for Alternatives 5
  - 2.3.1. Known Risks of CO_2 Fire Suppression 5
  - 2.3.2. Physiological Effects of CO_2 Exposure 6
  - 2.3.3. Safety Measures in Reclamation Facilities 7
  - 2.3.4. Limitations of Mitigation Measures 8

3.0 Suppression System Options 9

- 3.1. High- and Low-Pressure CO_2 Fire Suppression Systems 9
  - 3.1.1. System Design 10
  - 3.1.2. Properties and Advantages of CO_2 as an Extinguishing Agent 12
  - 3.1.3. Limitations and Hazards of CO_2 Systems 13
  - 3.1.4. Extinguishment with CO_2 13
  - 3.1.5. Summary of CO_2 Systems 13
- 3.2. Water-Based Fire Suppression Systems 15
  - 3.2.1. System Design 16
  - 3.2.2. Properties and Advantages of Water as a Extinguishing Agent 17
  - 3.2.3. Limitations and Challenges 18
  - 3.2.4. Extinguishing with Water 19
  - 3.2.5. Summary of Water-Based Systems 19

3.3. Water Mist Systems 20
  3.3.1. System Design 20
  3.3.2. Properties and Advantages 22
  3.3.3. Limitations and Challenges 22
  3.3.4. Extinguishment with Water Mist 22
  3.3.5. Summary of Water Mist Systems 23
3.4. Clean Agents 24
  3.4.1. System Design 25
  3.4.2. Properties and Advantages 28
  3.4.3. Limitations and Challenges 28
  3.4.4. Summary of Clean Agent Systems 29
3.5. Hybrid Fire Extinguishing Systems (Water Mist and Nitrogen) 29
  3.5.1. System Design 30
  3.5.2. Properties and Advantages 31
  3.5.3. Limitations and Challenges 31
  3.5.4. Extinguishment with Hybrid Media 31
  3.5.5. Summary of Hybrid Fire Extinguishing Systems 32
3.6. Dry and Wet Chemical Extinguishing Systems 33
  3.6.1. Dry Chemical Extinguishing Systems 33
  3.6.2. Wet Chemical Extinguishing Systems 33
  3.6.3. Application in Hydroelectric Generators 34
4.0 Agent and System Comparison 34
4.1. Reliability 35
4.2. Effectiveness 40
  4.2.1. Combustion and Extinguishment 40
  4.2.2. Key Attributes to Extinguishment 44
  4.2.3. Summary of Agent Effectiveness 45
4.3. Maintainability 48
4.4. Cost 49
4.5. Safety 51

5.0 System Selection 53
6.0 Conclusion 57
7.0 Path Forward 57
8.0 References 58

Tables

Table 1. —Acute health effects of high concentrations of carbon dioxide with increasing levels of concentration and exposure duration. 8
Table 2. —Summary of CO_2 system characteristics; strengths and limitations 14
Table 3. —Summary of water-based system characteristics; strengths and limitations 19
Table 4. —Summary of water mist system characteristics; strengths and limitations 23
Table 5. —Summary of clean agent characteristics; strengths and limitations 29
Table 6. —Summary of hybrid fire extinguishing systems characteristics; strengths and limitations 32
Table 7. —Suitability and Comparison of Dry and Wet Chemical Extinguishing Systems 34
Table 8. —Comparison of the reliability and success rate of various extinguishing systems and agents1 39
Table 9. —Key attributes to extinguishing diffusion flames and smoldering combustion and provides an importance factor to each. 45
Table 10. —Comparative ranking of each agent to effectively meet each key attribute required for extinguishment of flaming and smoldering combustion 46
Table 11. —Relative cost of each fire extinguishing system based on type 49
Table 12. —Comparative table for system selection based on agent type 53

Figures

Figure 1. —Typical high-pressure CO_2 system commonly found in Reclamation. 3
Figure 2. —Pie chart showing the percentage of incidents where carbon dioxide was intentionally and unintentionally released based on the EPA study. 6
Figure 3. —Typical high-pressure CO_2 system commonly found in Reclamation. 11
Figure 4. —Typical low-pressure CO_2 system commonly found in Reclamation. 12

Figure 5. —An automatic sprinkler head on a pre-action system inside an air-cooled generator. 16

Figure 6. —Typical pre-action deluge valve for water spray systems 17

Figure 7. —Example of an electric pump for high-pressure water mist systems. 21

Figure 8. —FM-200 system used to protect an oil storage room in a Reclamation power plant. 26

Figure 9. —Typical inert gas system installation. 27

Figure 10. —Hybrid fire extinguishing system used to protect a hydroelectric generator. 30

Figure 11. —Reliability Block Diagram showing component interactions of a hydroelectric generator extinguishing system and highlighting the boundaries of the system. 37

Figure 12. —Fire tetrahedron showing the four elements fuel, heat, oxygen, and chemical reaction required for sustained combustion 41

Executive Summary

This report evaluates alternatives to carbon dioxide (CO_2) fire suppression systems currently protecting hydroelectric generators in Bureau of Reclamation facilities. Many CO_2 systems are decades old, increasingly unreliable, and present severe risks to personnel due to asphyxiation hazards. Replacement parts are often unavailable, and outdated designs no longer align with modern safety codes.

The study compares a range of suppression technologies—including water-based, water mist, clean agents, inert gas, hybrid systems, and chemical agents—against criteria of effectiveness, safety, reliability, maintainability, and cost. While CO_2 remains effective for extinguishing fires, its life-safety risks and maintenance challenges make it unsustainable as a long-term solution.

Findings indicate that hybrid fire extinguishing systems utilizing a combination of inert gas and water mist show the greatest promise, offering effective extinguishment, improved safety, and lower long-term maintenance costs despite higher initial investment. Inert gas and water mist systems alone also provide viable alternatives, while halocarbon-based clean agents face regulatory phaseouts and chemical systems may be unsuitable for generator protection.

The report concludes that transitioning away from CO_2 toward hybrid fire extinguishing systems or single agent inert gas or water mist systems is the most prudent path forward to ensure safe, reliable, and sustainable fire protection for critical hydropower infrastructure.

1.0 Introduction

As early as 1984, the Bureau of Reclamation began evaluating alternatives to high-pressure carbon dioxide (CO_2) fire suppression systems (Chadwick, Osburn, & Klataske, 1984). In February of that year, Reclamation's Engineering & Research Center published the CO_2 Fire Protection Study for Hydrogenerators, which suggested a shift in fire suppression practices. The report indicated that future fire protection trends would likely favor Halon, water-based systems, or low-pressure CO_2 over high-pressure CO_2 systems. Notably, the 1984 report highlighted a significant risk of asphyxiation associated with CO_2 systems—even when they function as designed.

However, in the years following the report, one of the most promising alternatives—Halon—was phased out due to its environmental impact. The 1987 Montreal Protocol on Substances that Deplete the Ozone Layer, an international treaty aimed at protecting the ozone layer, led to the global phase-out of Halon production due to its high ozone-depleting potential (Office of Enviromental Quality, 2025). As a result, although Halon was initially viewed as a superior alternative, its long-term use was curtailed, limiting the range of viable fire suppression options.

Despite the known safety risks associated with CO_2 and due to the regulatory phase-out of Halon, the resulting Facilities Instructions, Standards, and Techniques (FIST) manual 5-12—developed in response to the 1984 study—continued to identify CO_2 as the only acceptable suppression method for generator protection for units over 10 megawatts (BOR, FIST 5-12, CO2 System Operation and Maintenace, 2005). Now, given the age and condition of the installed systems throughout Reclamation's powerplants, combined with evolving safety considerations, it is time for Reclamation to revisit and evaluate current fire suppression practices and to research alternative technologies that prioritize human safety without sacrifice to system performance. Hence, this study explores the currently available suppression systems that may replace Reclamation's current CO_2 systems.

1.1. Study Overview

This study evaluates the effectiveness, safety, reliability, maintainability, and relative cost of various fire suppression agents suitable for protecting hydroelectric generators. It draws on data from a recent survey of Reclamation power plants, supplemented by observations from site visits, to assess the current condition and performance of generator fire suppression systems in service today. The study also reviews trends and best practices from other agencies and organizations to validate and compare alternative suppression technologies. Additionally, it provides a selection table of suppression systems that highlights the pros and cons for each system type and identifies the suitability of an agent for use in a hydroelectric generator.

1.1.1. Key Topics Covered:

- A detailed comparison of suppression agents, including their history, extinguishing properties, and operational use.

- Discussion of reliability of a system to perform on demand based on the complexity of the system design, failure modes, and redundancies.
- Discussion of combustion types that may occur within a generator, and the distinction between "extinguishment" and "suppression"—a key consideration in system selection.
- Discussion of the effectiveness of each agent type to extinguish or suppress combustion inside a generator.
- A comparison of inspection, testing, and maintenance (ITM) of each system type and how that affects availability of the system.
- A relative cost comparison based on the installation, ITM of the system, and downtime including loss of generation.

1.1.2. Goals

This study serves as part of a decision-making process for selecting generator fire suppression systems. It includes a comparison chart outlining advantages and disadvantages of each agent type, offering a quick reference for system designers and plant managers.

The findings of this study are intended to support informed decision-making and guide potential revisions to existing FIST documents, ensuring they reflect current technologies, safety standards, and operational best practices.

2.0 Background

2.1. Reclamation CO_2 systems.

A 1941 article titled *"World's Largest Hydrogenerator Guarded Against Fire"* describes the installation of a high-pressure CO_2 fire suppression system at Grand Coulee Dam (Blonk, 1941). The article highlights the system's advanced automatic features for the time, including heat detectors—referred to by the author as "electric watchmen"—and protective relays that would trip instantly in response to fire or arc faults, triggering the release of CO_2. The system used explosive squibs—called "peace-time bombs" in the article—to open valves and release CO_2, promising to smother even the most severe fires within seconds.

The article accurately explains the fundamental operating principles of CO_2 systems: fire is extinguished by displacing oxygen and suppressing the flame, followed by cooling of generator windings through the formation of dry ice, which helps prevent reignition. This principle has formed the foundation of generator fire protection in Reclamation facilities for more than 80 years.

The physical layout of CO_2 systems described in the 1941 article remains largely representative of systems still used throughout Reclamation today, Figure 1. While certain components have been updated—such as replacing explosive squibs with electronic releasing valves and upgrading control panels with modern fire alarm releasing systems—much of the original circuitry remains in place. Additional safety features, including warning signage, wintergreen odorants, strobe beacons, and gas detection sensors, have been incorporated to improve occupant protection. In some plants, high-pressure systems have been replaced with low-pressure CO_2 systems to reduce maintenance demands. Nonetheless, the fundamental design and operational principles of the CO_2 suppression system has changed very little over the decades.

Figure 1. —Typical high-pressure CO_2 system commonly found in Reclamation.

Currently, CO_2 fire suppression systems are installed on all generators 10 megawatts or larger. According to the 1984 *CO_2 Fire Protection Study for Hydrogenerators*, 83 percent—or 162 of 195 units—were protected by CO_2 systems. These include 164 generators, 14 generator/motors, and 17 large motors (Chadwick, Osburn, & Klataske, 1984). Of these, approximately 70 percent use high-pressure CO_2, while the remaining 30 percent use low-pressure systems. A more recent survey of Reclamation facilities confirms that the number of systems and types of systems remains virtually unchanged.

While the exact dollar value of the protected units was not determined for the study, these 195 generator units represent a substantial investment—not only in equipment, but in power generation capacity. As such, any decisions regarding system replacement must be made with care. Emerging fire suppression technologies introduced since 1984 offer promising alternatives, with the potential for improved life safety, comparable or enhanced extinguishing effectiveness, reliable operation, and reduced long-term costs. These innovations warrant serious evaluation as Reclamation looks to modernize fire protection for its critical infrastructure.

2.2. Aging CO_2 Systems and Reclamation's Urgency for Action

The age of CO_2 fire suppression systems in Reclamation facilities ranges from the 1940s to the present day. While these systems have historically provided effective protection, their expected service life is typically 20 to 25 years (Bishop, 2017). Beyond this period, systems begin to face significant challenges related to obsolescence, reliability, and compliance.

As systems age, replacement parts become increasingly difficult to obtain. In many cases, components are no longer manufactured or supported by the original vendors. For example, explosive squibs, once common in early CO_2 systems, are no longer produced, making periodic testing and maintenance or repair impractical. This further affects the reliability of the systems and increases risk.

Compounding the issue, changes in fire protection codes and standards over the past several decades may render these older system designs obsolete, noncompliant, or over-engineered, leading to inadequate suppression, failure to operate, or increased maintenance costs. In some instances, ancillary systems such as plant fire alarm systems are modernized, while the core CO_2 suppression systems remain unchanged. This results in a mismatch—legacy CO_2 releasing panels, detectors, and relays often cannot communicate with newer alarm systems, creating safety and operational vulnerabilities.

The disconnect places plant personnel at increased risk, especially in the event of a fire. Despite these known limitations, many Reclamation facilities continue to rely on outdated CO_2 systems for generator protection.

It is important to recognize that fire is a common-cause failure mode that can critically affect complex systems. In the context of hydropower, generator fires not only threaten lives but also result in significant unit downtime, costly damage, and interruption of power generation.

Many Reclamation plants have begun procuring replacement systems, which can cost hundreds of thousands of dollars per unit. However, these replacements must be based on current technologies that provide improved safety, reliability, effectiveness, maintainability, and code compliance.

There is a clear and urgent need for Reclamation to conduct comprehensive research into alternative fire suppression methods for hydroelectric generators. The goal is to modernize outdated systems, enhance personnel safety, reduce operational risk, and ensure long-term sustainability of Reclamation’s power infrastructure. Pursuing this research may prevent future system failures—and potentially save lives.

2.3. CO_2 Fire Suppression – Hazards, Safety Measures, and the Case for Alternatives

2.3.1. Known Risks of CO_2 Fire Suppression

In 2000, the U.S. Environmental Protection Agency (EPA) published a landmark report, *Carbon Dioxide as a Fire Suppressant: Examining the Risks* (EPA, 2000). Widely cited in fire protection literature, the report highlighted the dangers associated with CO_2 suppression systems, particularly as alternatives to phased-out Halon systems.

Although not specific to hydroelectric generator protection, the report's conclusions are relevant to Reclamation’s use of CO_2-based systems:

- The minimum CO_2 concentration required to extinguish a fire—34% by volume—is well above lethal levels for humans.
- Adverse health effects begin at concentrations as low as 4%, with loss of consciousness occurring around 7%, and death likely within one minute at 17%.
- Between 1975 and 2000, 72 deaths and 145 injuries were attributed to CO_2 system discharges.
- Many of these incidents occurred during maintenance operations, due to system activation or leakage during access.

The breakdown of incidents from the EPA study is shown in Figure 2.

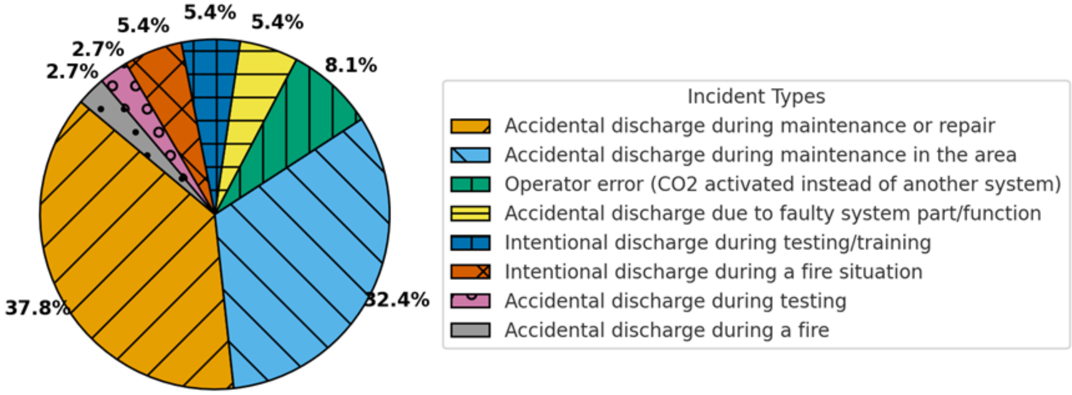

Figure 2. —Pie chart showing the percentage of incidents where carbon dioxide was intentionally and unintentionally released based on the EPA study. The most important value is the combined percentage of incidents during maintenance of 70.2 percent. (Reclamation)

Although Reclamation's CO_2 suppression systems have been relatively safe, with no fatalities and only a few minor injuries related to handling of the CO_2 cylinder since their installation began in the 1930s, the inherent danger posed by CO_2 exposure remains a serious concern.

2.3.2. Physiological Effects of CO_2 Exposure

Carbon dioxide is a familiar gas present in our daily lives. CO_2 is a colorless, odorless gas produced naturally by a variety of natural processes. Humans produce CO_2 through normal respiration. During respiration, CO_2 is expelled from the bloodstream into the lungs and then forced out of the body. This is all driven by partial pressure differences between the saturated CO_2 in the bloodstream and the free CO_2 in the lungs and air (Arthurs & Sudhakar, 2005).

Under normal conditions:

- Ambient air contains ~0.04% CO_2 (400 ppm), with a partial pressure of 0.041 kPa.
- Venous blood near the lungs contains CO_2 at 6.1 kPa, facilitating its diffusion from blood to air. A process essential to respiration and the uptake of oxygen to the blood (Arthurs & Sudhakar, 2005). In fact, the small amount of CO_2 present in our lungs improves the breathing process through the Bohr effect which regulates oxygen release in the blood (Butler & Tsuda, 2015).

As atmospheric CO_2 concentrations rise:

- At 4%, the diffusion gradient narrows, slowing removal of CO_2 from the body and causing symptoms like headache, sweating, and shortness of breath within minutes.

- At 7%, the gradient reverses, causing CO_2 to enter the bloodstream, potentially resulting in confusion and unconsciousness within 90 seconds.
- At 17%, respiratory function ceases entirely, and death occurs rapidly, even if oxygen levels remain within normal range (Arthurs & Sudhakar, 2005).

Table 1 describes the various effects of exposure to high levels of CO_2 at different atmospheric concentrations.

Reclamation's generator fire protection systems are typically designed for CO_2 concentrations of 50% by volume with holding times of at least 20 minutes—3 times the lethal limit and would cause immediate death if an individual were exposed.

2.3.3. Safety Measures in Reclamation Facilities

Reclamation employs multiple administrative and engineering controls to reduce the risk of CO_2 exposure, especially during maintenance:

- **Lockout/Tagout (LOTO) Procedures:**
  Maintenance operations follow formal lockout/tagout protocols to physically and electronically isolate the CO_2 system from generator enclosures (BOR, FIST 1-1, Hazardous Energy Control Program, 2019). These include:
  - Closing valves and disconnecting/capping piping.
  - Removing firing heads from CO_2 cylinders.
  - Bypassing detection zones on control panels.
- **Wintergreen Odorant:**
  A distinct scent additive is included in CO_2 systems to provide olfactory indication of CO_2 discharge. The sense of smell is very powerful and often will be noticed before auditory or visual indications. Personnel are trained to evacuate immediately if they detect the smell of wintergreen (BOR, FIST 1-1, Hazardous Energy Control Program, 2019).
- **Gas Detection and Alarm Systems:**
  Many facilities are equipped with CO_2 monitoring systems, particularly in turbine pits and at the cylinders or bulk tank. These systems include:
  - Audible alarms and visual beacons triggered at the lowest threshold CO_2 level 5000 ppm (International Code Council, 2017).
  - Remote annunciation in the control rooms allowing operators to initiate evacuation.
  - System integration with plant fire alarms for automatic notification and signal transmission to monitoring locations.

- **Evacuation and Reentry Protocols:**
  Following any system discharge—whether accidental or due to a fire—facilities are fully evacuated. Reentry is permitted only after clearance by emergency responders using self-contained breathing apparatus (SCBA) and confirming that air quality is within safe limits.

Table 1. —Acute health effects of high concentrations of carbon dioxide with increasing levels of concentration and exposure duration.

Concentration of Carbon Dioxide in Air (%)	Exposure Time	Effects
2	Several hours	Headache, dyspnea upon mild exertion
3	1 hour	Dilation of cerebral blood vessels, increased pulmonary ventilation, and increased oxygen delivery to the tissues
4 – 5	Within a few minutes	Mild headache, sweating, and dyspnea at rest
6	1 – 2 minutes <16 minutes Several hours	Hearing and visible disturbances Headache and dyspnea Tremors
7 – 10	Few minutes 1.5 minutes—1 hour	Unconsciousness or near unconsciousness Headache, increased heart rate, shortness of breath, dizziness, sweating, rapid breathing
10 – 15	1+ minute	Dizziness, drowsiness, severe muscle twitching, and unconsciousness
17 – 30	<1 minute	Loss of controlled and purposeful activity, unconsciousness, convulsions, coma, and death.

Source: EPA 430-R-00-002, February 2000.

2.3.4. Limitations of Mitigation Measures

Despite rigorous protocols, the risk posed by CO_2 exposure is only mitigated—not eliminated. Leaks, system faults, or procedural lapses can occur unexpectedly, particularly during maintenance or testing. Lapses in required inspection, testing, and maintenance of CO_2 systems contribute to the problem further by hiding potential equipment failures from discovery. Drills and exercises simulating a CO_2 discharge are not part of the safety planning and training. This can result in complacency or confusion in a real event. Ultimately, even when all the mitigation strategies are in place, CO_2 is toxic and the release of the agent at any time introduces a new safety hazard.

CO_2 is still potentially the most effective agent for extinguishing generator fires—but this effectiveness comes with a high cost in human safety risk. This tradeoff raises the central issue and the subject of this study:

> **Is the risk to human life justifiable given available alternatives?**

3.0 Suppression System Options

The available suppression systems for most industrial fire applications include:

- High- and low-pressure CO_2 systems
- Water-based systems which include automatic sprinkler systems and water spray systems
- Water mist systems
- Clean agent systems that use inert gases
- Clean agent systems that use halocarbons
- Hybrid systems that combine inert gas with water
- Dry and wet chemical systems

This list not an exhaustive list of all suppression systems nor does it provide information of the diversity that exists within each group. The following sections of the report provide more detail and quickly identify systems or system types that could be considered for use in a hydroelectric generator and conversely identify those types that should not be considered. Ultimately, any alternative to CO_2 that can provide equal or better performance and can do so within the risk parameters decided upon by the stakeholders is an acceptable alternative to CO_2.

3.1. High- and Low-Pressure CO_2 Fire Suppression Systems

Carbon dioxide has been associated with fire suppression since the earliest designs of modern fire extinguishers, though it was not originally used as the extinguishing agent itself. Initially, CO_2 served as a propellant. In 1881, Almon M. Granger patented the soda-acid fire extinguisher, which relied on a chemical reaction between sulfuric acid and a sodium bicarbonate solution. This reaction produced CO_2 gas, which pressurized the extinguisher to discharge water onto a fire (Fire Ranger, 2019).

Over time, the unique extinguishing properties of CO_2 were recognized and exploited. The gas began to be used directly—first in handheld fire extinguishers, and later in fixed fire suppression systems. Between 1910 and 1915, the first CO_2 fire suppression systems were installed in Europe and later adopted in the United States. These systems were developed in response to the growing need for non-conductive fire suppression, particularly in electrical environments. One early adopter was Bell Telephone, which sought an alternative to water-based systems that could safely extinguish fires near energized equipment (Wyscocki, 2017).

In 1917, the Walter Kidde Company developed the first integrated smoke detection and CO_2 suppression system for use aboard ships. CO_2 systems offered a non-damaging, effective alternative to water-based systems (Kidde, 2025). By the 1930s, CO_2 suppression systems were being designed and installed to protect enclosed hydroelectric generators.

3.1.1. System Design

High-pressure systems are more common than low-pressure designs. High pressure systems consist of several cylinders connected to a manifold, Figure 3, whereas low-pressure systems use a bulk tank to store the CO_2, Figure 4. Both systems are connected to a series of pipe and routed through valves to the generator air housing. The nozzles are installed along a ring header above the stator coils to apply the CO_2 directly into the combustion zone.

Figure 3. —Typical high-pressure CO_2 system commonly found in Reclamation. Multiple CO_2 cylinders are connected by hoses to a common manifold.

Figure 4. —Typical low-pressure CO_2 system commonly found in Reclamation. A large bulk tank contains all the CO_2 for initial and extended discharge. Routing is in the large red cabinet behind the tank.

3.1.2. Properties and Advantages of CO_2 as an Extinguishing Agent

CO_2 possesses several physical and chemical properties that make it well-suited for generator protection:

- Noncombustible and Chemically Stable: Does not react with most materials.
- Stored Energy for Discharge: Stored as a pressurized liquid, requiring no pumps or external power for release.
- Non-Conductive: Safe for use on energized electrical equipment.
- Residue-Free: Leaves no residue after discharge, minimizing post-incident cleanup.
- Penetration Capability: As a gas, it can reach tight, enclosed areas within generators.

- Cost-Effective and Readily Available: Widely used across industries, making it economical and accessible.

3.1.3. Limitations and Hazards of CO_2 Systems

Despite its strengths, CO_2 presents critical limitations, particularly regarding personnel safety and system maintenance:

- **Toxicity at Effective Concentrations:**
  Lethal exposure levels are inherent in the concentrations required for fire suppression—typically 34% to 50% by volume—making accidental human exposure potentially fatal.
- **Enclosure Integrity Is Critical:**
  The protected area must be tightly sealed to retain CO_2 at extinguishing concentrations. Leaky enclosures reduce effectiveness and can result in system failure.
- **Labor-Intensive Maintenance:**
  CO_2 systems require routine weighing of cylinders and regular inspection of valves and seals. Other suppression agents do not share this requirement.
- **Specialized Training Required:**
  Proper inspection, testing, and maintenance demand qualified personnel with CO_2-specific system knowledge.

3.1.4. Extinguishment with CO_2

CO_2 systems extinguish fires primarily through oxygen displacement. The agent is discharged into the protected space and rapidly displaces the air, reducing the oxygen concentration below the level required to sustain combustion.

When released, CO_2 transitions rapidly from liquid to gas, resulting in a measurable temperature drop. This leads to the formation of dry ice, which assists in:

- Cooling the fire zone
- Reducing surface temperatures
- Preventing reignition of solid fuels

3.1.5. Summary of CO_2 Systems

Table 2 provides a summary of high- and low-pressure CO_2 systems.

Table 2. —Summary of CO_2 system characteristics; strengths and limitations

Category	Strengths (Pros)	Limitations (Cons)
Suppression Mechanism	- Proven, long history of use - Effective via oxygen displacement, cooling	- Lethal at suppression concentrations
Compatibility	- Electrically non-conductive - No residue - Safe for energized equipment	- Requires tight enclosure for effectiveness
System Design	- Flexible application (total flood, local application)	- Requires rigorous safety protocols
Cost and Supply	- Low agent cost - Readily available - Reasonable installation cost	- Ongoing maintenance (cylinder weighing)
Personnel Safety	- Wintergreen odorant and detection systems provide warning	- Requires LOTO, evacuation, and SCBA for safety

3.2. Water-Based Fire Suppression Systems

Water-based fire suppressions use water as the primary extinguishing agent and include:

- **Automatic sprinkler systems:**
  Mechanically actuated, hydraulically calculated fire suppression systems that discharge water upon thermal activation of individual sprinkler heads. Types include:
    - Wet pipe systems are the most common and always contain water in the pipes, ready for immediate discharge when a sprinkler head activates.
    - Dry pipe systems are filled with pressurized air or nitrogen, which is released when a sprinkler activates, allowing water to flow in—ideal for unheated areas where pipes might freeze.
    - Pre-action systems require a two-step activation: a separate detection system must first sense a fire and open a valve before water enters the pipes, reducing the risk of accidental discharge in sensitive areas like data centers.
- **Water spray/ deluge systems:**
  Engineered suppression systems that utilize non-automatic, open nozzles arranged to deliver water to specific hazard areas through directional discharge patterns.
- **Water mist systems:**
  Specialized fire suppression systems that discharge water as a fine mist or fog.
  NOTE: Due to the unique properties of water mist application, further discussion about these systems is a separate section of the report.

Water-based systems have a long history in fire protection. These systems have been in use for over a century, with the first patent issued in 1872 to Phillip W. Pratt and refined in the 1890s by Frederick Grinnell into a design that closely resembles modern-day sprinklers. Water spray systems are the second most used suppression system behind CO2 for generator fire protection (Dieken, 2011). However, the use of automatic sprinklers for enclosed generators is less common and when used, they are pre-action systems, Figure 5.

Figure 5. —An automatic sprinkler head on a pre-action system inside an air-cooled generator. The sprinkler head is shown installed directly above the stator coils. (Dieken, 2011).

3.2.1. System Design

Automatic sprinklers and water spray systems are connected to a fixed water source. This may be an unlimited source like the penstock or to a water tank sized to accommodate the system. Water passes through control valves to the sprinklers or spray nozzles. Automatic sprinklers employ a fusible link or glass bulb that keeps the sprinkler closed until sufficient heat melts or breaks the bulb opening the sprinkler head. Pre-action systems and water spray systems use a deluge valve that must be activated electronically to permit water to enter the generator. Sprinklers or spray nozzles are installed above the stator to ensure water is delivered into the combustion zone Figure 6.

Figure 6. —Typical pre-action deluge valve for water spray systems This system uses an electronic solenoid to initiate the system pneumatically. The photo also shows the manual override switch.

3.2.2. Properties and Advantages of Water as a Extinguishing Agent

Water-based suppression systems offer several key benefits:

- **Proven effectiveness:**
  Water is the most used fire suppression agent worldwide effective across a wide range of fire types, particularly Class A combustibles such as wood, plastics, and electrical windings (when de-energized) (Sardqvist, 2002).
- **Superior Cooling Properties:**
  A single gallon can absorb approximately 9,280 BTUs (2,586.5 kJ) of heat when raised from 70°F to 212°F and vaporized into steam—over four times the energy absorption of any other nonflammable liquid (Sardqvist, 2002). This makes water especially effective

in suppressing smoldering or deep-seated fires by rapidly cooling fuel below pyrolysis temperatures (typically 482°F to 842°F / 250°C to 450°C) (Yu & Newman, 2008).

- **Abundant and readily available:**
  Most hydroelectric facilities have easy access to large volumes of water, making it a practical and sustainable suppression resource.
- **Low cost and common components:**
  Water-based systems use widely available parts and piping, resulting in lower installation and maintenance costs compared to gas- or chemical-based systems.
- **Flexible application methods:**
  Water systems can be configured for total flooding or local application. They can use varying size nozzles or emitters that provide precise control of flow and distribution patterns. Droplet size can be controlled from large rain like drops to fine mists or fog, depending on the fire hazard and system design.

3.2.3. Limitations and Challenges

Despite their many strengths, water-based suppression systems present specific limitations that must be considered, particularly in hydroelectric applications:

- **Water quality requirements:**
  While water is generally available at hydroelectric plants, it may be unsuitable for direct use due to high mineral content, sediment, or contamination. In such cases, filtration, softening, or the use of a dedicated treated water supply (e.g., tank storage) may be necessary.
- **Pressure and flow constraints:**
  Sufficient water pressure is critical for effective suppression. If plant water pressure is inadequate, fire pumps may be required to meet design specifications. This adds to system complexity, upfront cost, and ongoing maintenance demands.
- **Potential for equipment damage:**
  In contrast to clean agents like CO_2, water may cause thermal shock, electrical faults, or corrosion when sprayed on sensitive generator components—unless the system is carefully engineered to mitigate these risks (Delcourt, 2006) e.g. proper nozzle placements, power shutdown prior to release, and use of deionized water.
- **Flooding:**
  Areas around and below the generator can experience flooding. The drains and sump pump system may not be able to handle the large volume of water. Other equipment may be damaged. Cleanup will be more extensive.
- **Post Discharge Considerations:**
  Returning the unit to service will require drying out the generator prior to energizing. Additional testing of the insulation system must be performed. Combined these things add significant downtime and loss of power generation.

3.2.4. Extinguishing with Water

Water-spray systems primarily extinguish fire cooling the flames and blocking the radiant energy to the surrounding fuel. When the droplets are introduced into the combustion zone, the water must be heated to the same temperature of the flame for combustion to continue. The water droplets that impinge and collect on the fuel surfaces must be evaporated away before the underlying fuel can be heated to the ignition point.

Overall, water extinguishes fire through several mechanisms:

- Direct cooling of the flame front and burning material
- Cooling and wetting of combustible surfaces to prevent reignition
- Steam generation, which displaces oxygen and inhibits combustion
- Blocking radiant heat transfer, reducing thermal feedback to adjacent surfaces
- Dilution of flammable vapors (particularly for water-soluble fuels)

3.2.5. Summary of Water-Based Systems

Table 3 provides a summary of water-based systems.

Table 3. —Summary of water-based system characteristics; strengths and limitations

Category	Strengths (Pros)	Limitations (Cons)
Suppression Mechanism	- Superior cooling properties - Displace oxygen through steam generation - Absorb and block radiant heat - Physically smothers flames	- Less effective on Class B pool fires
Compatibility	- Water may pose no or little risk to equipment if quality is good	- Conductive; requires electrical shutdown
System Design	- Flexible application (total flood, local application)	- May require a fire pump which adds cost and complexity
Cost and Supply	- Low agent cost - Readily available - Low installation cost	- May require a storage tank or filter system
Personnel Safety	- 100% safe to personnel	- Clean up essential to avoid slips and falls

3.3. Water Mist Systems

Water mist systems are specialized fire suppression systems that discharge fine water droplets, defined by NFPA 750 as sprays in which 99% of the volume consists of droplets less than 1,000 microns in diameter (NFPA 750-Water Mist Fire Protection Systems, 2019). These systems combine elements of water spray, automatic sprinkler, and clean agent systems, offering versatility in both local application and total flooding configurations.

In recent years, water mist systems have had a resurgence making them appear rather new, yet, they have been around as long as any other water-based system. Around 1880, F.E. Meyers created a backpack that was pierced with a lance to produce fine water droplets for fighting small forest fires. In 1890, Grinnell helped to patent H.S. Parmelee's "pepper pot" water mist nozzle. Innovations in mist nozzle design during the 1930s and 1940s led to the emergence of multi-orifice nozzles such as Lechler's "water dust" nozzle resembling nozzles used today (Mawhiney & Back III, 2016).

3.3.1. System Design

Water mist systems are the most diverse systems in this study. Water mist systems can be mechanically or electrically activated. Systems can be designed for:

- Total flooding of enclosed volumes (e.g., generator air housings)
- Local application for cable trays, lube oil systems, or bearing housings

Systems can be closed nozzle (pre-action) systems similar to sprinklers where nozzles activate thermally to release mist into protected space or open nozzle (deluge) where water is released upon valve actuation via detection system. They can operate at various pressures:

- Low-pressure: < 12.1 bar (175 psi)
- Intermediate-pressure: 12.1–34.5 bar (175–500 psi)
- High-pressure: > 34.5 bar (>500 psi)

Water may be delivered using:

- Municipal or building water pressure
- Electrically or diesel-driven pumps (Figure 7)
- Compressed gas propellants (e.g., nitrogen)

Water droplet size can vary from 10 microns to 1000 microns depending on the application.

Systems installed in generator spaces typically use a detection system connected to a releasing panel that opens a control valve. The system uses high pressure and fine spray nozzles (20-30 microns) and uses either a pump or high-pressure nitrogen cylinders to drive the water. Once the water enters the air housing, open nozzles positioned either above the stator or around the air distribute the mist throughout.

Figure 7. —Example of an electric pump for high-pressure water mist systems.

3.3.2. Properties and Advantages

Water mist systems maximize the properties of water as an extinguishing agent. Water mist has the same basic advantages of any water-based system. However, finely divided water mist introduces new aspects especially around cooling effects and the ability to dilute and displace oxygen in the combustion zones. The smaller droplet size of water mist absorbs heat faster than traditional water spray by providing more surface area. This also leads to more steam production especially in hot environments with active flames. The steam production from water mist systems is sufficient to displace oxygen in the enclose to below the lower flammability level of the fuel.

Other advantages include using less water to achieve the same results, thus reducing the cleanup and dry out time and cost. Water is nontoxic and water mist systems can be used in occupied spaces.

3.3.3. Limitations and Challenges

Water mist system performance depends on precise design. There is no universal nozzle arrangement or droplet size optimal for all generator types. Effectiveness is sensitive to pre-burn conditions, ventilation, and compartment geometry. Even with fine sprays, water mist systems may not penetrate deep into the windings making it less effect for smoldering combustion. Water mist like all water-based systems is conductive and require unit shutdown prior to application.

3.3.4. Extinguishment with Water Mist

Water mist extinguishes fires through five interrelated mechanisms:

1. Gas-phase cooling – Water droplets absorb heat from hot combustion gases, vaporizing into steam and reducing flame temperatures.
2. Oxygen displacement and vapor dilution – Steam displaces air and interrupts the flammable fuel-air mixture.
3. Fuel surface cooling and wetting – Droplets contacting hot surfaces lower surface temperatures, reducing pyrolysis.
4. Radiation attenuation – Suspended mist scatters and absorbs radiant heat, reducing thermal feedback.
5. Kinetic effects – Droplet momentum disrupts flame structure and slows combustion.

In enclosed generator compartments, water mist systems are particularly effective due to the controlled volume and limited ventilation. As droplets vaporize:

- Steam reduces oxygen content: A reduction of ~10% O_2 can occur in a 100 m^3 space with 5.5 liters of fully vaporized water.

- Expansion of steam (approx. 1,700:1 volume ratio) disrupts air entrainment and flame stability.
- Vapor mixing inhibits re-ignition by displacing air and absorbing residual energy.

At localized levels, the mist plume can dilute fuel vapors below their lower flammability limit.

3.3.5. Summary of Water Mist Systems

Table 4. —Summary of water mist system characteristics; strengths and limitations

Category	Strengths (Pros)	Limitations (Cons)
Suppression Mechanism	- Exceptional cooling properties - Displace oxygen through steam generation up to 10% - Dilutes fuel vapors - Blocks radiant heat - Physically disrupts flame	- Complex designs specific to each application - Not ideal for deep-seated fires
Compatibility	- Fine droplets may pose no or little risk to equipment especially with deionized water	- Conductive; requires electrical shutdown
System Design	- Flexible application (total flood, local application)	- May require a fire pump - Pneumatic systems require compressed gas storage and maintenance
Cost and Supply	- Low agent cost - Readily available - Moderate design and installation cost	- May require a storage tank or dedicated water supply
Personnel Safety	- 100% safe to personnel	

3.4. Clean Agents

Clean agents are gaseous fire suppression chemicals designed to extinguish fires without leaving residue, causing equipment damage, or posing risks to occupants in normally occupied spaces. They are commonly used in applications where electrical equipment, delicate machinery, or irreplaceable assets must be protected and post-discharge cleanup must be minimized.

These agents gained prominence following the global phase-out of Halon 1301 and Halon 1211, which were widely used for high-value asset protection until they were identified as ozone-depleting substances under the Montreal Protocol (1987).

The loss of Halons spurred a decades-long effort to develop environmentally sustainable, electrically non-conductive, and low-toxicity alternatives. The result was the emergence of two primary categories of clean agents:

1. Halocarbon-based agents – such as FM-200 and Novec 1230
2. Inert gas systems – using blends of nitrogen, argon, and sometimes CO_2

Table 5 provides a list of the most common commercially available clean agents on the market. This study focuses on FM-200 (HFC-227ea), Novec 1230 (FK-5-1-12), and the inert gases Nitrogen (N_2), Argon (Ar), and related blends)

Table 5. ––Commercially available clean agents

Chemical Name	Trade Name	ASHRAE Designation	Chemical Formula
Heptafluoropropane	FM-200	HFC-227ea	CF_3CHFCF_3
Trifluoromethane	FE-13 FE-13TM Fluoroform	HFC-23	CHF_3
Chlorotetrafluoroethane	FE-24 FreonTM	HFC-124	$CHClFCF_3$
Pentafluoroethane	FE-25	HFC-125	CHF_2CF_3
Dodecafuoro-2-methylpentan-3-one	Novec 1230	FK-5-1-12mmy2	$CF_3CF_2C(O)(CF(CF_3))_2$
Hexafluoropropane	FE-36	HFC-236fa	$CF_3CH_2CF_3$
Trifluoroiodide	Triodide	FIC-13I1	CF_3I
N_2/Ar/CO_2	Inergen	IG-541	N_2 (52%)

Chemical Name	Trade Name	ASHRAE Designation	Chemical Formula
			Ar (40%) CO_2 (8%)
N_2/Ar	Argonite	IG-55	N_2 (50%) Ar (50%)
Argon	Argon	IG-01	Ar
Nitrogen	Nitrogen	IG-100	N_2

3.4.1. System Design

3.4.1.1. *FM-200 (HFC-227ea)*

FM-200, or **heptafluoropropane (HFC-227ea)**, was introduced in the early 1990s by Great Lakes Chemical (now part of Chemours) as one of the first widely adopted Halocarbon replacements. It is a colorless, odorless gas stored as a liquid under pressure and vaporized upon discharge.

The systems usually consist of tanks that store the agent connected to a pipe system routed into the protected space. The agent discharges through emitters or heads that distribute the agent throughout, Figure 8 shows a typical tank and pipe arrangement. FM-200 systems are activated both manually and automatically through a releasing panel. Timed abort switches are often installed to temporarily delay discharge until occupants can exit the space. FM-200 is safe for occupants even at design concentrations, but the gas can be irritating to some and is overall unpleasant.

3.4.1.2. *Novec 1230 (FK-5-1-12)*

Novec 1230, developed by 3M in the early 2000s, is a fluorinated ketone that represents a newer generation of synthetic clean agents. It is stored as a liquid and vaporizes upon discharge.

Like FM-200 the systems usually consist of a tank where the agent is stored. This is attached to a pipe network that enters the protected space. Nozzles distribute the agent throughout the space. The system is activated either manually or automatically by a detection system and the agent is discharged via a releasing panel. Momentary abort switches are used to delay discharge until occupants exit the protected area since the release through the nozzles tends to be extremely loud and upsetting.

Figure 8. —FM-200 system used to protect an oil storage room in a Reclamation power plant. . The photo shows a typical installation with bulk agent tanks with releasing heads installed on top of the tanks and the piping to the protected space.

3.4.1.3. *Inert Gas Systems (IG-55, IG-100, IG-541)*

In 1972, H.W. Carhart and G.H. Fielding proposed the use of nitrogen gas fire suppression systems for use in submarines as an alternative to CO_2 due to the obvious confined space in a submarine. Later in 1994, Carhart and Fielding suggested the use of nitrogen as an alternative to Halons in all applications.

Inert gas systems use naturally occurring gases primarily nitrogen and argon, and in some cases small amounts of carbon dioxide are used. The systems can be designed to use a single gas. The cost of argon lends itself to be blended with other gases. The most common systems use:

- IG-100: 100% nitrogen
- IG-55: 50% nitrogen / 50% argon
- IG-541 (Inergen®): 52% nitrogen / 40% argon / 8% CO_2

The addition of CO_2 may seem odd, but experiments have shown that a small amount of CO_2 helps individuals caught in the protected space to breathe a little easier in the reduced oxygen environment.

Systems consist of high-pressure cylinders connected to a single manifold, Figure 9. This is connected to a pipe network that leads into the protected space and the agent is distributed through nozzles. Nozzle placement would be similar to CO_2 systems to provide faster knockdown of flaming combustion.

Figure 9. —Typical inert gas system installation. The system shown in the picture is an Inergen gas system recognizable from the green top of the cylinders (FST, n.d.)

3.4.2. Properties and Advantages

The number one advantage of clean agents is the ability to extinguish fire and leave zero residue on electrical equipment. Clean agents are safe for occupied spaces even at design concentrations. They are nonconductive which means equipment does not need to be deenergized prior to application. FM-200 and Novec 1230 can be discharged rapidly, less than 10 seconds in some designs.

3.4.3. Limitations and Challenges

Currently clean agents are not listed for use in hydroelectric generators. This does not eliminate them from being used. It requires more effort to get approvals.

FM-200 has a high global warming potential of ~3,220 which makes it subject to regulatory scrutiny under the Kigali Amendment to the Montreal Protocol, prompting the industry to develop lower-impact alternatives.

Novec 1230 has a low environmental impact, but the production of the agent involves generating higher than acceptable level of polyfluoroalkyl substances (PFAS). As a result, 3M has ceased production.

For use in hydroelectric generators successful extinguishment will depend on enclosure tightness and for systems other than inert gas, volume could be a limiting factor.

3.4.4. Summary of Clean Agent Systems

Table 5. —Summary of clean agent characteristics; strengths and limitations

Category	Strengths (Pros)	Limitations (Cons)
Suppression Mechanism	- FM- 200: Cooling -Novec 1230: Cooling and flame inhibition -Inert Gases: Displace oxygen -	- Not ideal for deep-seated smoldering fires
Compatibility	- Nonconductive	
System Design	- Flexible application (total flood, local application)	- Complex designs specific to each application - Subject to regulatory restrictions
Cost and Supply	- FM-200 and Novec 1230 have high agent costs - Inert gases have moderate agent cost - Moderate design and installation cost	- FM-200 and Novec 1230 may be phased out and become unavailable in U.S. market.
Personnel Safety	- 100% safe to personnel within NOAL limitations	-Can be acoustically unpleasant during discharge

3.5. Hybrid Fire Extinguishing Systems (Water Mist and Nitrogen)

Hybrid fire extinguishing systems (hybrid) represent a significant advancement in fire protection technology, combining the benefits of water mist and inert gas suppression. These systems are designed to address the limitations of traditional suppression methods, particularly in environments where water damage or chemical residue is unacceptable.

These systems were first developed in the early 1990’s. The revelation came when the research showed that combining the cooling effects of ultrafine water mist and the dilution of oxygen with inert gases was more effective than either system on its own.

3.5.1. System Design

Hybrid systems are self-contained and provide the agent for extinguishment and the means to transport it to the generators without the use of pumps. A bank of high-pressure nitrogen cylinders provides the inerting gas and pushes the water from the storage tank that is integrated into the system, Figure 10. These systems use a routing valve that controls the flow and pressure of the nitrogen gas for optimum effect. The nitrogen and the water travel to the generator in separate pipes. The water and nitrogen are mixed at the emitters that are designed to atomize the water to 10 microns creating a fog infused with nitrogen gas.

Hybrid systems are actuated by a detection system via a releasing panel. Unlike other extinguishing systems, hybrid systems typically use cross-zoning to limit activation to two independent events occurring before release. This reduces the chance of false alarms and accidental discharge.

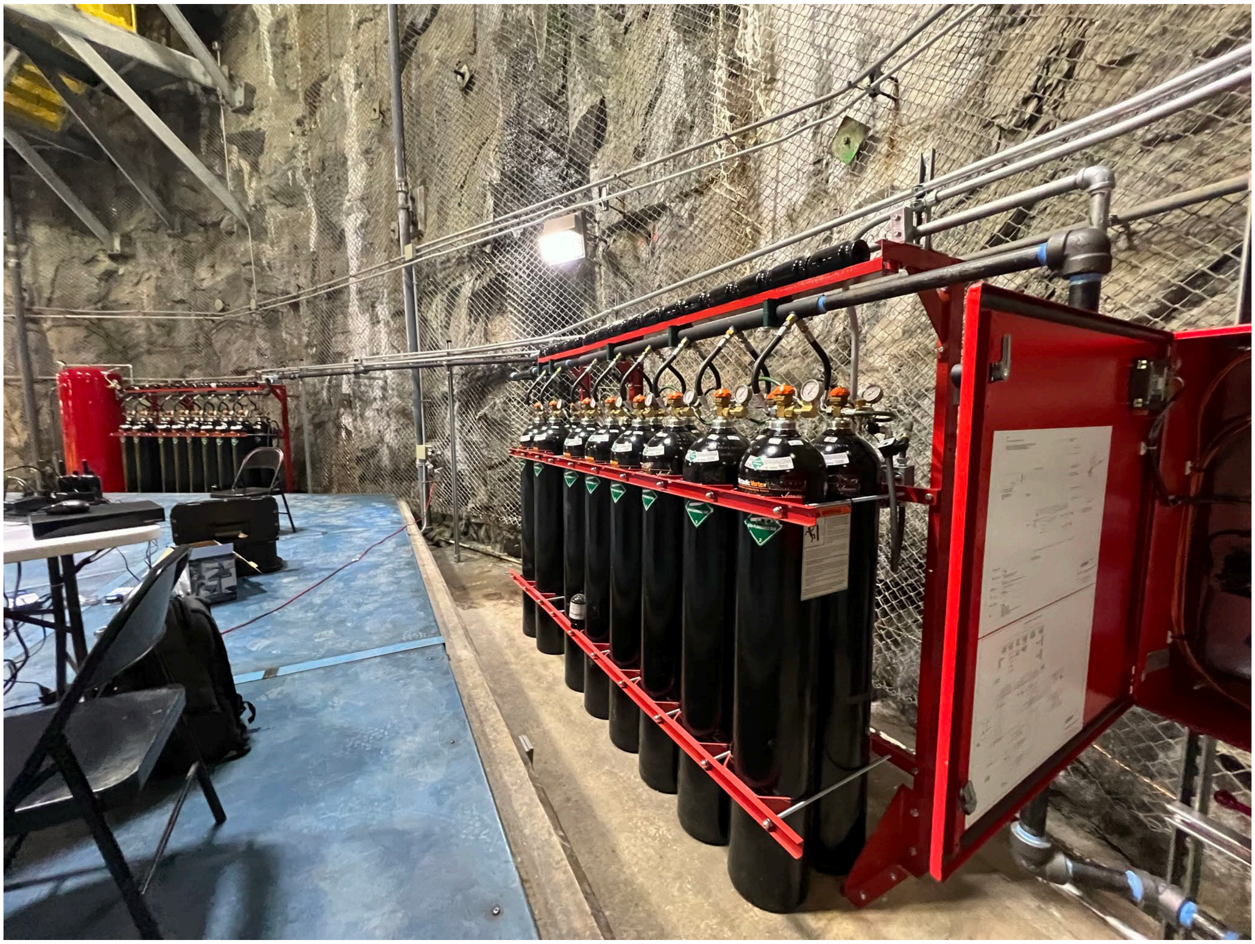

Figure 10. —Hybrid fire extinguishing system used to protect a hydroelectric generator. Photo shows the typical installation with banks of nitrogen tanks connected to a single manifold. The water tank is in the red cylinder in the background.

3.5.2. Properties and Advantages

Hybrid systems have properties that separate them from traditional clean agent system or water mist systems. The way in which the nitrogen and water are combined enhances the properties of each. Nitrogen is already close in density to air which means it is relatively buoyant neutral. However, the ultra-fine water droplets become encapsulated by the nitrogen in the mixing property which make the overall particle bigger. This slows down the diffusion rate which means the agent holds inside the air housing longer and prevents the reentry of oxygen. This same process increases the penetration ability of the water to reach areas inside the generators that would normally be shielded like the combustion zone. This means that emitters can be placed in more convenient locations and not buried under steel plates, making them easier to inspect and service.

Other advantages include:

- Safe to personnel even in occupied areas
- Agent requirements are inexpensive
- Smallest amount of water used for any system. Typical system use is 50 to 100 gals which is 100 time less than water spray systems
- Water poses no ill effects on electrical equipment

3.5.3. Limitations and Challenges

Hybrid systems still have some challenges that need to be considered.

- Water is conductive and unit shutdown required
- Specialized design and installation requirements
- Limited manufacturers
- Cross zoning may delay activation and more damage to unit may occur
- Short history of use and incident data is very limited

3.5.4. Extinguishment with Hybrid Media

Hybrid systems utilize a dual-agent approach to suppress fires effectively through the following mechanisms:

1. Cooling- Fine water mist droplets absorb heat from the fire, reducing the temperature below the combustion threshold. Droplets are typically less than 10 microns in diameter, maximizing surface area for heat absorption.
2. Oxygen Displacement- Inert gases (commonly nitrogen) are discharged to reduce the oxygen concentration in the protected area. Oxygen levels are lowered below the threshold required to sustain combustion (typically <15%).

3. Kinetic Distribution- The high-velocity discharge of the gas-water mixture ensures uniform distribution throughout the enclosure. This penetrates the flame zone knocking down the flame. This enhances the system's ability to suppress fires in complex geometries or ventilated spaces.
4. Agent Retention- continues to inert the atmosphere sufficiently to prevent reignition without second application.

3.5.5. Summary of Hybrid Fire Extinguishing Systems

Table 6. —Summary of hybrid fire extinguishing systems characteristics; strengths and limitations

Category	Strengths (Pros)	Limitations (Cons)
Suppression Mechanism	- Exceptional cooling properties - Displace oxygen through introduction of inert gas - Dilutes fuel vapors - Blocks radiant heat - Physically disrupts flame	- Complex designs specific to each application - Longer time to full concentration level are met - Cross-zoning may delay activation
Compatibility	- Ultras-Fine droplets pose no or little risk to equipment especially with deionized water	- Conductive; requires electrical shutdown
System Design	- Flexible application (total flood, local application)	- Requires two sets of pipe runs (water and gas)
Cost and Supply	- Low agent cost - Readily available - Moderate design and installation cost	- Higher initial costs - Limited providers May require a storage tank or dedicated water supply
Personnel Safety	- 100% safe to personnel	

3.6. Dry and Wet Chemical Extinguishing Systems

3.6.1. Dry Chemical Extinguishing Systems

Dry chemical fire suppression systems emerged prominently in the mid-20th century as a response to the growing need for rapid, localized fire suppression in industrial and commercial environments. These systems utilize finely powdered chemical agents—most commonly monoammonium phosphate or sodium bicarbonate—discharged under pressure to interrupt the chemical reaction of a fire. The agent is stored in pressurized tanks and released through a piping network or directly from portable extinguishers.

Dry chemical systems are particularly effective against Class A (ordinary combustibles), Class B (flammable liquids), and Class C (electrical) fires. Their rapid knockdown capability and non-conductive properties make them suitable for high-risk areas such as fuel storage rooms, electrical panels, and engine compartments. However, they leave a significant residue that can be corrosive or damaging to sensitive equipment, which limits their use in environments requiring clean agent solutions.

In hydroelectric generator facilities, dry chemical systems may be used in auxiliary spaces such as control rooms, battery banks, or transformer enclosures where rapid suppression of electrical fires is critical. However, due to the potential for equipment contamination, their use is typically limited to non-critical or isolated compartments.

3.6.2. Wet Chemical Extinguishing Systems

Wet chemical systems were developed primarily to address the unique hazards of commercial kitchen fires, particularly those involving cooking oils and fats (Class K fires). These systems gained traction in the 1990s as commercial cooking operations expanded and traditional suppression methods proved inadequate. The extinguishing agent is a potassium-based solution that reacts with hot grease to form a soapy layer (saponification), effectively cooling and smothering the fire.

Wet chemical systems are typically pre-engineered and activated either automatically via heat detection or manually. They are designed to discharge directly over the hazard through nozzles strategically placed in hoods and ducts. The agent is non-toxic and minimally corrosive, making it safe for use in food preparation areas.

While not traditionally associated with hydroelectric facilities, wet chemical systems could find niche applications in on-site cafeterias or food service areas within large power generation campuses. Their use in generator halls or turbine enclosures is not recommended due to incompatibility with electrical and mechanical systems.

3.6.3. Application in Hydroelectric Generators

Overall, due to the corrosive nature of dry and wet chemicals, it is not recommended that they be used inside a hydroelectric generator. The clean up efforts could potentially cause more damage to the generator than the initial fire. Dry and wet chemicals do not offer any significant advantage over any other extinguishing agent to warrant the ancillary damage to the generator. Table 7 provides a comparison and compatibility of dry and wet chemicals.

Table 7. —Suitability and Comparison of Dry and Wet Chemical Extinguishing Systems

Feature	Dry Chemical	Wet Chemical
Development Period	1900s–1960s (NFPA codified by 1970s)	1960s–1990s (UL 300 codified in 1994)
Typical Agents	MAP, Sodium/Potassium Bicarbonate, PK	Potassium Acetate, Carbonate, Citrate
Fire Classes	A, B, C (agent-dependent)	Primarily K; limited B
Mechanism of Action	Flame inhibition, particulate blanketing	Saponification, surface cooling, vapor sealing
Residue	Heavy particulate; requires mechanical cleanup	Liquid; runoff and potential corrosion
Electrical Suitability	No – nonconductive but residue is damaging	No – water-based and conductive
Compatibility with Generators	Poor – high risk of damage	Not applicable
Advantages	Fast knockdown, wide application, low cost	Effective for grease fires, low re-ignition risk
Disadvantages	Residue, corrosiveness, respiratory hazard	Conductive, corrosive, limited applicability

4.0 Agent and System Comparison

To properly differentiate agents from one another, the parameters for comparison must be established. These can be different for the different stakeholders involved. The parameters that are of interest to fire protection engineers the most are effectiveness, reliability, and compliance with codes and standards. The parameters that most often concern end users are reliability, maintainability, cost, and safety. Together, the parameters that form the basis of comparison in this study are as follows:

- **Reliability:** The ability of the system to confidently operate as intended when required.
- **Effectiveness:** The ability of the extinguishing agent to extinguish a fire inside the generator.
- **Maintainability:** The effort required to inspect, maintain, and test the system ensuring a reliable system.
- **Cost:** Includes upfront installation, lifetime inspection and maintenance, training, restoration and downtime costs.
- **Safety:** Includes exposure hazards, occupational hazards, mitigation requirements and procedures.

The focus is on comparing the unique properties of each system and associated agent. Reliability is based on the typical system design layouts and common activation methods described in industry codes and standards and common practices. Effectiveness is based on the unique properties of each agent independent of the system design by assuming that proper delivery of the agent is always achieved. Maintainability is based on codified methods and frequencies plus an estimate of the time required to properly inspect, test, and maintain the system which affects the availability of the system. All of which corresponds back to reliability. Cost is based on the relative costs of each system and not on actual cost estimates. Safety looks at the hazards associated with the agent as well as potential hazards when working with or around the systems. Machine integrity looks at the potential for damage to the generator and associated components during normal operations including normal activation and maintenance over the lifetime of the machine.

4.1. Reliability

Reliability is a key concern for both fire protection engineers and end users, though their expectations of reliability differ slightly. Fire protection engineers define reliability as the system’s ability to consistently perform its life safety and asset protection functions. For end users, reliability means the system operates as expected, without failures or disruptions, and minimizes the likelihood of false alarms. Engineers view a reliable system as one that activates when needed, as delays can lead to larger fires, greater damage, and even the failure to control and contain the fire within the prescribed space. End users, on the other hand, see a reliable system as one that swiftly extinguishes the fire on demand, thus building confidence in its performance. End users seek assurance that the system reduces damage, repair costs, and downtime, ultimately lowering overall expenses. Both groups agree that failure to activate the system is unacceptable, as it could result in loss of life or complete asset destruction—outcomes that are intolerable. By combining these perspectives, reliability can be defined as confidence in a system's ability to effectively respond to a fire when needed, safeguarding life and property while minimizing damage and costs.

For many, personal experience shapes their confidence in a system—if their experience is positive, they consider the system reliable. Personnel experience, though trusted by the individual, is not quantifiable and is as such not the best judge of reliability. Others may rely on independent agencies or professional organizations to conduct testing, gather data, and publish the results. overall reliability scores like those reported in the NUREG/CR-6850 (NUREG/CR-6850, 2005):

- Carbon dioxide = 96%
- Halon (clean agent) systems = 95%
- Wet pipe sprinkler systems = 98%
- Deluge or pre-action sprinkler systems = 95%

However, the data from NUREG does not clearly include maintenance contributions to unavailability, credit for manual actuation of the system, variations in system activation, human dependent failures, and plant specific data.

The National Fire Protection Agency provides reliability data for some systems by tracking the National Fire Incident Reporting System (NFIRS) (Hall, Ph.D., 2006). NFIRS has tools for tracking the types of fires and suppression systems used to extinguish them. Data from the 2006 report indicates that sprinkler systems are only 93% reliable with 65% of those that failed were due to the system being shut off. This highlights the difference in reliability when you consider human interactions with the system.

Reliability block diagrams (RBD) are often used to determine system reliability. RBDs use a forward analysis based on the probability of success. Figure 11 shows a RBD for a typical generator extinguishing system. It is applicable to CO_2 systems, clean agent systems, water mist and deluge systems.

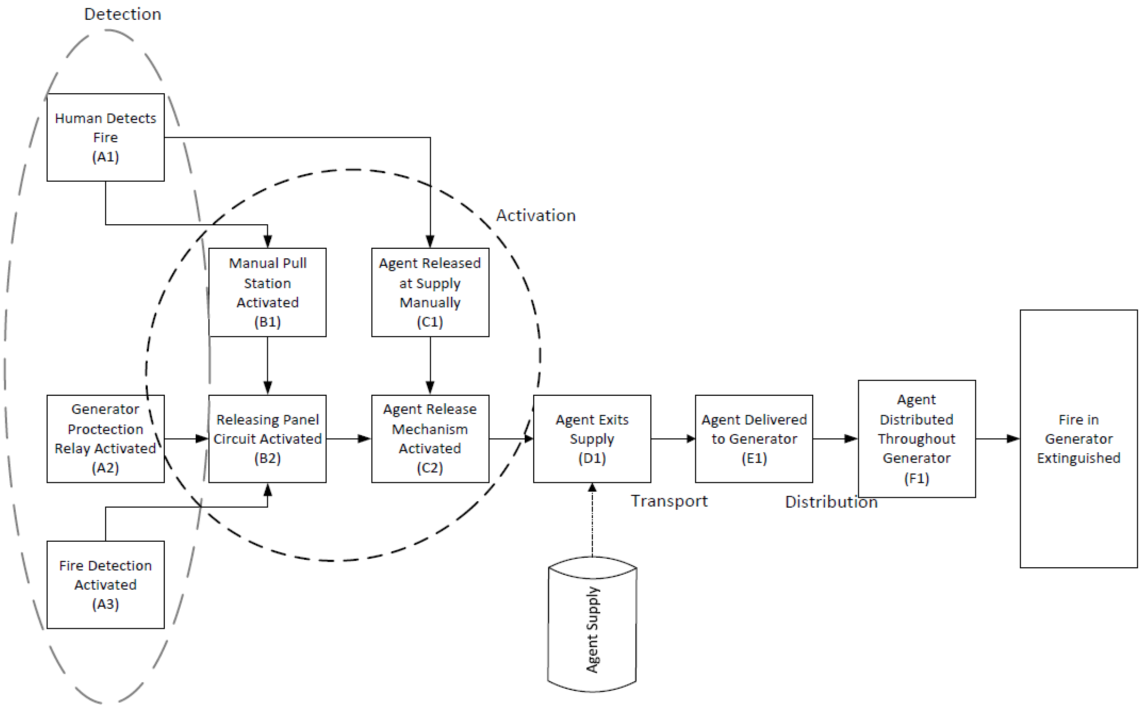

Figure 11. —Reliability Block Diagram showing component interactions of a hydroelectric generator extinguishing system and highlighting the boundaries of the system.

The figure also includes the identification of the basic components that make up any extinguishing system which include:

- **Agent supply**- tanks, cylinders, water supplies.
- **Agent transport**- valves, pipes, connections.
- **Agent delivery and distribution**- sprinklers and nozzles.
- **Detection**- thermal devices, smoke detectors, generator protection systems.
- **Activation**- releasing panels, manual release stations, mechanical switches, solenoids.
- **Human Interactions**- detection and activation of the system, maintenance of the system, inspection and testing of the system.

A complete failure in any one of the components will prevent the system from working. A partial failure in one of the systems can render the system unsuccessful in extinguishing the fire. The success rate of each component is determined by collected data, manufacturer testing, Failure Mode and Effects Analysis (FMEA), or good engineering judgement.

Another way to look at reliability of the system is to focus on the potential of failure of a specific top event. In this study, the top event is “Suppression system fails to extinguish the generator fire”. The most common tool to analyze top event failure is with a fault tree. A fault tree graphically models all the parallel and sequential combinations of faults that will result in the system failing to perform as expected. Fault trees offer a way to quantify the reliability by using the failure rate or percentage likely of a failure to occur over the lifespan of the system. Like RBDs, these can be based on published failure data, relative severity based on engineering experience or determined through methods like FMEA. The main advantage of fault tree analysis is the ability to include the effects of availability, human engagement, and outside influences into the system.

Based on a comprehensive review of various sources that included compiled data from system-based studies, RBD analyses, fault tree analyses, and industry reports, Table 8 is a comparative table of the reliability and success rate of different suppression system and agents.

Table 8. —Comparison of the reliability and success rate of various extinguishing systems and agents1

System / Agent Type	Typical Reliability	Success Rate
CO_2 Systems	85–95%	80–90%
Wet Pipe Sprinkler Systems	96–99%	85–95%
Dry Pipe Sprinkler Systems	90–95%	80–90%
Pre-action Sprinkler Systems	90–98%	80–90%
Deluge Systems	85–95%	90–100%
Water Mist Systems	90–98%	80–95%
Clean Agent Systems (e.g., FM-200, Novec 1230)	95–99%	85–95%
Clean Agent Systems (e.g., Inert Gas, N_2, Ar)	95–99%	85–95%
Hybrid Extinguishing Systems[2]	93–99%	Unknown
Dry Chemical Systems	90–95%	80–90%
Wet Chemical Systems	85–95%	90–100%
Manual Fire Extinguishers[3]	Highly variable	50–90%

1-Values in table are based on compiled data from system-based studies, RBD analysis, fault tree analyses, and industry reports.
2- Hybrid extinguishing system data is limited to laboratory experiments only. No data on real life fire events.
3- Manual fire extinguishers are not part of this study. Data is included for completeness.

4.2. Effectiveness

Effectiveness is the ability of the agent, when reliably introduced into the environment, to achieve the desired outcomes and results, in this case, extinguishing a generator fire. Effectiveness can be subjective, as it often varies depending on individual opinions or shifts in goals and objectives. For this study, effectiveness is defined as the ability of an agent to extinguish flaming combustion and retard the rate of smoldering combustion. It is important to note that the system design is not a factor in the ability of an agent to extinguish a fire. The assumption is that the system is designed and installed to properly deliver the agent as intended at levels or concentrations expected or as dictated by codes and standards.

The best measure of effectiveness is through quantitative methods that are produced in a controlled experiment. Unfortunately, a comprehensive experiment testing each extinguishing agent for use in a generator has not been performed nor was such an experiment part of this study. This does not mean that relative effectiveness of each agent cannot be determined.

Qualitative methods can evaluate the relative importance of various extinguishing factors that contribute to fire suppression. For each extinguishing agent, these factors are identified and compared by examining their use in other fire scenarios documented in various studies and articles. The significance of each factor is then assessed across different potential fire scenarios within a generator. This process yields a relative score for each agent allowing for a comparative evaluation of their overall effectiveness.

4.2.1. Combustion and Extinguishment

To understand the effectiveness of each agent in extinguishing a fire, it is necessary to understand the type of fire and combustion methods of each fuel type present in the generator. Any fire relies on the concept of fuel, oxygen, and sufficient heat are all present and in close enough proximity to initiate combustion and that a self-sustained chemical reaction is required to continue the combustion process. This is often shown as the fire tetrahedron, Figure 12. Based on this concept, the underlying science of extinguishment rests on the following principles:

1. For combustion to take place, an oxidizing agent, a combustible material, and an ignition source in sufficient quantities are essential.
2. The combustible material must be heated to its piloted ignition temperature before it can be ignited or can support the spread of flame.
3. Subsequent burning of a combustible material is governed by the heat feedback from the flames to the pyrolyzing or vaporizing combustible.
4. The burning will continue until one of the following happens:
    a. The combustible material is consumed.
    b. The concentration of oxidizing agent (normally, oxygen in the air) is lowered to below the concentration necessary to support combustion.

c. Sufficient heat is removed or prevented from reaching the combustible material, thus preventing further fuel pyrolysis or vaporization.
d. The flames are chemically inhibited or sufficiently cooled to prevent further reaction (Yu & Newman, 2008).

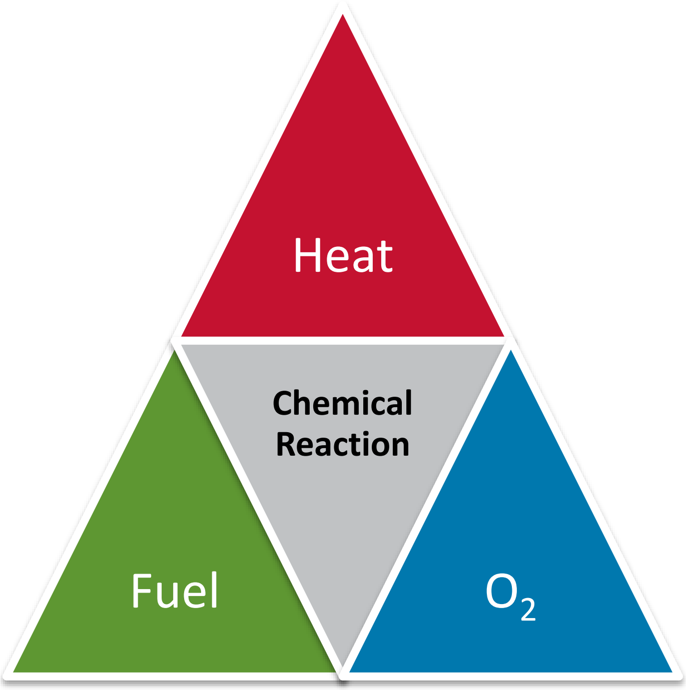

Figure 12. —Fire tetrahedron showing the four elements fuel, heat, oxygen, and chemical reaction required for sustained combustion

Fires occur in generators because the first principle may be conceptually the easiest form of fire prevention, in practice the separation of fuel, oxygen, and heat is impossible.

The fuel sources inside a hydroelectric generator include:

- Winding insulation. Asphalt-mica or thermoset, either polyester or epoxy resin-impregnated mica tape
- End turn insulation, including varnish tape, varnish on fiberglass tape, and mica on paper backing
- Fiberglass end shields
- Cables
- Current or potential transformers
- Lubricating oil
- Contamination: brake dust, insulation materials, outside materials (FM Global, 2020).

The source of oxygen is just air. The source of ignition is from the large amount of electrical energy present. This can arc releasing large amounts energy instantaneously or thermal loading of the electrical components like windings, cables, and transformers through resistance.

The fuel sources can be simplified to solid polymer combustibles (thermoset insulation), liquid polymers (asphalt-mica, cable insulation), and Class IIIB combustible liquids (lubricating oil). All will produce flaming combustion. The compact, tight arrangement of the stator coils lend itself to smoldering combustion. Each type of combustion requires a different approach to extinguishment.

4.2.1.1. *Flaming Combustion*

Flaming combustion, especially diffusion flames like those of burning solids and combustible liquids, is more sensitive to different extinguishing methods than premixed flaming or smoldering combustion. This is in part due to the processes of pyrolysis and gasification of solid fuels and the vaporization of liquid fuels. Both require the heating of the surface of the base fuel to the point where flammable vapors are released and continue to be released. Thus, cooling the fuel and fuel surface sufficiently will extinguish the fire. This can be done directly by contact of the extinguishing agent like water to the surface cooling by conduction, cooling the air that passes over the surface removing heat through convection, or by blocking the radiant energy from the flame to the fuel surface. Additionally, applying water to the surface of a solid or liquid will physically block the flammable gases from mixing with the air, smothering the fire.

Diffusion flames are also sensitive to disruption of the flame temperature. In general, the heat produced by the chemical reaction of burning is absorbed by the unreacted reactants, combustion products (soot, smoke, etc..), dilutants (naturally occurring), the air not entrained, and the surrounding surfaces. The flames must produce enough energy to overcome the losses to keep combustion going.

The introduction of gaseous compounds like N_2 dilute the flammable vapors and displaces oxygen in the form of air out of the combustion zone. The effect is not chemical but physical. For the reaction to continue, the N_2 needs to be heated to the same temperature as the combustion reactants. This begins to cool the flame temperature. Cooling the air that is entrained into the combustion zone has the same effect.

The reaction between the combustible gases and the oxygen is chemical. The movement of oxygen and combustible gases is mechanical. The rate of the chemical reaction (chemical timescale) normally is much faster than the rate with which the combustible gases are transported into the combustion zone (mechanical timescale). When a dilutant like CO_2 is introduced, the amount of present oxygen in the combustion zone is reduced, increasing the timescale for the reaction to take place. If the chemical timescale is as long or longer than the mechanical timescale, the flames will extinguish.

Related to reaction rates and heat absorbed by combustion byproducts, some suppression agents work by interfering with the chemical reaction directly by creating additional compounds. These formation of these compounds steals energy form the system reducing the heat production and slows the reaction rate.

The most effective way to extinguish flaming combustion is to attack the flame directly by reducing the production of flammable gases or lowering the flame temperature. The most direct way to reduce the concentration of flammable gases is by cooling the fuel and the easiest way to cool the flame temperature is to dilute the flammable gases or introduce an agent that removes heat from the combustion reaction.

4.2.1.2. *Smoldering Combustion*

Smoldering combustion is a slow, low temperature, flameless burning of porous fuels like the winding insulation found inside the generator. Smoldering is dominated by oxidation of the fuel in a solid phase in contrast to flaming combustion which is dominated by gas phase combustion. Smoldering burns at much lower temperatures, 450°C to 700°C, than flaming combustion at 1500°C, and the heat release rate of smoldering combustion at the burning front is low 10 to 30 kW/m^2. This means that smoldering is a creeping fire that consumes solid fuel at a rate of 1 mm/min which is two orders of magnitude slower than flaming combustion. The most important difference between smoldering and flaming combustion is that smoldering can persist at oxygen levels as low as 8% whereas flaming combustion cannot occur below 14% for most fuels.

Smoldering combustion can be very difficult to extinguish. Oxygen removal is only effective if the low levels are maintained until the fuel bed is sufficiently cooled to prevent reignition when oxygen is reintroduced. This emphasizes the importance of integrity of the air housing to prevent leakage of the suppression gas. Ultimately, cooling the fuel bed is the only way to extinguish a smoldering fire but even this can hard. In experimental fires with heaps of coal, extinguishment required large amounts of water. The problem is that even though smoldering is a surface phenomenon, the surface in question may be deep in a channel or crack in the fuel bed essentially shielded from the suppression agent.

4.2.1.3. *Protection Relays and Extinguishment*

Generator protection relays are an important aspect to extinguishment in the generator. The protection relays automatically take a generator offline essentially removing power to the generator. Since, the most likely cause of ignition comes from an electrical fault or thermal loading from the electrical current, the first and best step in extinguishment is to remove energy from the fire zone. This ties back to the first principle of fire extinguishment by removing one part of the combustion process. The fire can only persist from the energy produced from the combustion reaction. In some cases, this may be sufficient for the fire to self-extinguish even without the use of a fire suppression agent. Regardless of the agent used, the most effective method of extinguishment starts with taking the generator offline. For some agents, like water, it is a necessity.

4.2.2. Key Attributes to Extinguishment

To extinguish a fire inside the generator, an agent must possess several key attributes that make the agent effective against diffusion flames and smoldering combustion. Table 9 summarizes these attributes for both diffusion flames and smoldering combustion. The effectiveness of each agent in this study can be based on the following key attributes:

1. **Cooling Capacity:** reduce the temperature of the fuel surface and surrounding gases below the ignition point through:
    a. Conduction: Direct contact with the fuel (e.g., water on a solid surface)
    b. Convection: Cooling the air that passes over the fuel
2. **Penetration Ability:** access the flame base and fuel surface effectively
3. **Oxygen Displacement:** reduce oxygen concentration to below fuel's lower flammability limit and dilute fuel vapors
4. **Chemical Inhibition:** interfere with the flame chemistry and slow or stop the chain reaction through:
    a. Formation of radical scavengers
    b. Energy absorption through chemical reactions that reduce flame propagation
5. **Radiant Heat Blocking:** preventing radiant heat from reaching the fuel surface and surrounding objects
6. **Fuel Surface Coverage:** to smother the fuel bed and block entrainment
7. **Heat Absorption Rate:** quickly remove heat from the combustion zone
8. **Re-wetting / Moisture Retention:** prevent re-ignition after initial suppression
9. **Agent Longevity:** ensure the agent remains effective over time and under various conditions

Table 9 summarizes the key attributes and how they apply to each agent or system type.

Table 9. —Key attributes to extinguishing diffusion flames and smoldering combustion and provides an importance factor to each.

Attribute	Diffusion Flames	Smoldering Combustion
Cooling Capacity	**High** — needed to cool flame and fuel surface to stop vapor production	**High** — needed to cool deep-seated heat and prevent re-ignition
Penetration Ability	**Moderate** — surface-level flame interaction	**High** — must reach deep into porous or layered materials
Oxygen Displacement	**Important** — displaces O_2 in flame zone (e.g., CO_2, N_2)	**Critical** — isolates fuel from air to stop surface oxidation
Chemical Inhibition	**Very effective** — interferes with flame chemistry (e.g., halons, dry chem)	**Less effective** — oxidation is surface-based and slower
Radiant Heat Blocking	**Useful** — prevents heat feedback to fuel surface	**Less relevant** — no flame radiation present
Fuel Surface Coverage	**Important** — smothers flame and blocks vapor release (e.g., foam, water film)	**Critical** — isolates smoldering surface from air
Heat Absorption Rate	**High** — needed to reduce flame temperature quickly	**High** — needed to absorb residual heat in fuel matrix
Re-wetting / Moisture Retention	**Moderate** — helps prevent re-ignition	**High** — essential to prevent re-smoldering
Agent Longevity	Short-term application may suffice	Long-lasting effect needed to prevent re-ignition

4.2.3. Summary of Agent Effectiveness

Table 10 presents a comparative summary of each suppression agent's effectiveness, based on its ability to meet the key performance attributes outlined in Table 9.

Table 10. —Comparative ranking of each agent to effectively meet each key attribute required for extinguishment of flaming and smoldering combustion

Agent	Cooling Capacity	Penetration Ability	Oxygen Displacement	Chemical Inhibition	Radiant Heat Blocking	Fuel Surface Coverage	Heat Absorption Rate	Re-wetting / Moisture Retention	Agent Longevity
Carbon Dioxide	Moderate	High	Very High	n/a	Very low	Low (dry ice formation)	Moderate	n/a	Moderate (requires tight enclosure and second application)
Water Spray (automatic or deluge)	High	Moderate	Low	n/a	Low	High	High	High	High (surfaces only)
Water Mist	High	Moderate to high (depends on droplet size)	Moderate to high (depends on droplet size and ambient temperatures)	n/a	Moderate to high (depends on level of steam formation)	Moderate to high	High	Moderate	Moderate (mostly on surfaces)
Nitrogen or Argon	Low	High	High	n/a	Very low	n/a	Low	n/a	Moderate (requires tight enclosure and potential second application)
Hybrid	High	High	High	n/a	Moderate	Low to moderate (depends on ambient temperature and	High	Low	High (neutral buoyancy creates long retention times without reapplication)

Agent	Cooling Capacity	Penetration Ability	Oxygen Displacement	Chemical Inhibition	Radiant Heat Blocking	Fuel Surface Coverage	Heat Absorption Rate	Re-wetting / Moisture Retention	Agent Longevity
						application rate.			
FM-200 (HFC-277ea)	High	High	Low	n/a	n/a	n/a	High	n/a	Moderate (requires tight enclosure)
Novec 1230 (FK-5-1-12)	Very High	Moderate	Low	n/a	n/a	n/a	Very High	n/a	Moderate (requires tight enclosure)
Dry Chemical[1]	Low	Low	Moderate (smothering effect)	High	High	High	Low	n/a	High
Wet Chemical[2]	Moderate	Low	Low	Low	Moderate	Moderate	Low	Moderate	Moderate

1- Dry Chemical extinguishing systems leave heavy residues on all surfaces and are not recommended for use in hydroelectric generators.

2- Wet Chemical extinguishing systems are intended for use with Class F fires that involve flammable liquids and are not recommended for use in hydroelectric generators.

4.3. Maintainability

Maintainability refers to the ease and the time required to inspect, test, and maintain the system. Inspections are visual examinations of a system verifying that the system appears to be in operating condition and is free of physical damage. Testing is a procedure used to determine the status of a system as intended by conducting periodic physical checks. Maintenance is the work performed to keep equipment operable and to execute repairs when necessary.

Inspections on each of the systems are relatively quick compared to testing or maintenance. However, system complexity and physical arrangement of components can make inspections difficult. In some cases, part of the system cannot be inspected until the unit is down for normal maintenance and even then, may take special considerations to accomplish— nozzles above the stator may require plates to be removed by crane to observe. The more components to a system the longer it will take to walk down a system. Additionally, some system components require more periodic inspection if electronic supervision is not provided— sprinkler valves that are unsupervised require inspection weekly versus quarterly for electronically supervised. Hybrid systems involve two sets of pipes into the generator, doubling the inspection effort.

Testing can be the most complex aspect of maintainability. Each system type has different requirements to verify the functionality. Some require full discharge of the system like deluge systems whereas automatic sprinklers can discharge water through a test valve eliminating the presence of water in the generator. Gas based systems and clean agents use a "puff test" to confirm operation. This may require accessing the nozzles to install bags that inflate during the testing or in the case of CO_2, air monitors may be installed to confirm the small amount of CO_2 released. The time related to testing can be greatly increased because of how the system is tested. Machine downtime is also a consideration especially if the testing does not coincide with planned outages.

In addition to the way in which each test can be performed, the persons conducting the test must be qualified to perform the test. Finding qualified individuals for certain systems can be difficult. Automatic sprinkler systems have the least level of knowledge required to test and thus there are many individuals qualified to test the system. Hybrid, on the other hand, is far less used than other system with far fewer qualified individuals to properly test these systems. This adds to the difficulty and the ability to properly test hybrid systems.

Periodic maintenance for most of the systems is similar. For example, all gas and pneumatic systems will have the same cylinder hose test and certification requirements. High-pressure CO_2 systems have the additional task of having to weigh the cylinders to confirm agent quantity. This makes high-pressure CO_2 the most labor intensive of all the systems to maintain. Another example, the maintenance on water-based system valves is the same across all system types with the notable exception of automatic sprinklers. These systems do not have a deluge valve requiring breakdown and resealing which reduces the overall maintenance requirement. In fact, automatic sprinkler systems are the easiest systems to maintain.

4.4. Cost

The cost of a system can be divided into three main categories: upfront installation, lifetime inspection, testing, and maintenance, and restoration and downtime costs. Installation costs vary based on the size and complexity of the system. For example, an automatic sprinkler system, which typically includes valves, pipes, and sprinklers, is relatively simple to install, with easily sourced parts and minimal labor requirements, making it a lower-cost option. In contrast, a hybrid extinguishing system requires separate valves and piping for nitrogen and water, a water tank, multiple nitrogen cylinders, proprietary nozzles, control valves, and a releasing panel with detection systems. The hybrid extinguishing system is significantly more complex, therefore, as to be expected more expensive to install.

Lifetime inspection and maintenance costs are also influenced by system complexity, as well as the knowledge, training, and potential certification requirements for personnel. Additionally, the expected lifespan of the system and its components affects these costs, as some systems may require more frequent part replacements. For example, piping and nozzles can last 50 to 60 years, whereas, releasing panels will need replacement every 15-20 years.

Restoration and downtime costs depend on both normal and unexpected system operations. These costs are further impacted by any loss in generation capacity. Periodic ITM for many systems would require a full clearance on the generator and given the location of nozzles and emitters may requiring disassembly of the generator. This leads to extended downtime, more loss in generation, more staff time to complete. Systems like high-pressure CO2 systems require significantly more time in maintenance related to weighing bottles.

Table 11 provides a relative cost for each system type based on data from project estimates, NFPA ITM tables and references, and pricing available on the internet.

Table 11. —Relative cost of each fire extinguishing system based on type

System Type	Installation and Design	ITM	Restoration	Notes
High- Pressure CO_2 Systems	Moderate	Very High- weighing cylinders	Low- if spare cylinders are available	CO_2 is inexpensive and readily available
Low-Pressure CO_2	Moderate	Moderate- includes refrigerant	Very Low- if tanks design is for multiple discharges	Refilling is done with a truck delivery and may not be available in remote areas

System Type	Installation and Design	ITM	Restoration	Notes
Wet Pipe Sprinkler Systems	Low	Low	Moderate- may require disassembly to replace sprinkler as they are one use only.	Parts are easily sourced, and spare heads are required by cod to be on site.
Dry Pipe Sprinkler Systems	Low	Moderate- includes air compressor in design	Moderate- same concerns as Wet-Pipe	Testing will require draining of the system
Pre-action Sprinkler Systems	Moderate- includes releasing panel and detection system	Moderate to High	Moderate- same concerns as Wet-Pipe	More time involved during testing as multiple activations are required.
Deluge Systems	Low to Moderate	Moderate	Moderate to High- significant dry out time required.	Installation and design cost dependent on complexity. Water management critical.
Water Mist Systems	Moderate to High- depends on complexity of design	Moderate to High	Moderate- Dry out time is critical	Complexity and the use of pumps or pneumatic system large factor in cost
Clean Agent Systems (e.g., FM-200, Novec 1230)	Moderate- design requires software.	Moderate to High- agent discharge not required during testing, machine access problematic	Moderate- dependent on agent availability	Agent costs are very high compared to inert gases or CO_2
Clean Agent Systems (e.g., Inert Gas, N_2, Ar)	Moderate	Moderate to High- machine access problematic	Low to Moderate- low if spare cylinders on-site	Agent cost is low if locally available

System Type	Installation and Design	ITM	Restoration	Notes
Hybrid Extinguishing Systems[2]	High- proprietary designs and equipment	Moderate to High- complex detection systems add to the cost	Moderate- requires dry out and PI testing	Agent costs are low, added maintenance due to water and gas separate

4.5. Safety

Safety is a complex and often debated topic, which can sometimes hinder discussions about the best solutions for a facility or plant. For the purposes of this study, safety will be limited to the impact of each agent on individuals exposed during normal operation, unexpected operation, and system failures. The following discussion focuses on the level of risk and the effort required to mitigate it, rather than attempting to predict the probabilities of exposure.

As described in detail earlier in this report as well being the thrust of the purpose of the report, CO_2 is a significant hazard to personnel at every stage of contact. Maximum effort is applied including procedures, documentation, training, equipment, safety systems all to mitigate the very possibility of exposure to CO_2. Other agents in this study are often touted as being 100% safe to personnel. This is not entirely true.

The toxicity of CO_2 is the major concern. Even at concentration levels of 1% per volume, there is some effect on the human body. Asphyxiation from CO_2 is not just the result of a lack of oxygen but the starvation of oxygen from the blood stream. Other extinguishing agents do not pose this risk (Harrington & Senecal, 2016).

Clean agents like FM-200 and Novec 1230 present a different health hazard— Cardiac sensitization. When cardiac sensitization occurs, even normal or slightly elevated levels of epinephrine (such as during stress or exercise) can trigger dangerous arrhythmias, including ventricular fibrillation, which can be fatal. The effects can happen within minutes of exposure.

Two safety points are used to describe the cardiotoxicity and allowable exposure limits to clean agents. The no observed adverse effect level (NOAEL) is the highest concentration of agent at which no adverse cardio effect occurred, and the lowest observed adverse effect level (LOAEL) is the lowest concentration at which an adverse cardio effect was measured. For FM-200 the NOAEL is 9% per volume and the LOAEL is 10.5% per volume which is higher than the design concentration of 7.9% per volume. More notable, the NOAEL and LOAEL for Novec 1230 is 10% per volume and >10% per volume, respectfully, which is much higher than the design concentration of 5.3%. Designs often employ predischarge alarms to minimize or eliminate exposure time. Keeping the design concentration below the LOAEL is key. Though it is permissible to design the system to the limit of the LOAEL if evacuation can be achieved in under 60 seconds (DiNenno & Forssell, 2016).

Inert gases create reduced oxygen environments which if the occupant cannot exit may cause permanent damage or potentially death. Exposure times to reduced oxygen environments are described by gas concentrations per volume. for gas concentrations up to 43 % (a residual oxygen concentration of 12 %), exposure time is limited to 5 minutes. For agent concentrations between 43 % and 52 % (12 % and 10 % residual oxygen concentration), the exposure time is limited to 3 minutes. For concentrations greater than 52 %, exposure time is limited to 30 seconds. In a strange twist, a small amount of CO_2 added to inert gases substantially reduces the hypoxic effects and improves respiration in low oxygen environments (DiNenno & Forssell, 2016).

Generators have complex geometry that can greatly interfere with exiting the space. The same geometry can interfere with rescue efforts as well. This suggests that even though clean agents are often thought to be nontoxic, lockout tagout procedures may still be required and recommended thus not reducing the mitigation strategies for service and maintenance (BOR, FIST 1-1, Hazardous Energy Control Program, 2019). Pre-discharge alarms and signal beacons required for clean agents are the same as the requirements of CO_2. The difference in ancillary equipment and systems is minimal between clean agent and CO_2. This is different for water-based systems that do not have the same restrictions because water is 100% non-toxic.

5.0 System Selection

Table 12. —Comparative table for system selection based on agent type

Criteria	CO_2 (High- and Low-pressure)	Water Spray/ Automatic Sprinklers	Water Mist	Clean Agents (FM-200, Novec 1230)	Inert Gas (IG-100, IG-55, IG-541)	Hybrid Systems	Dry Chemical	Wet Chemical
Fire Classes	A, B, C	A, B (limited)	A, B, (limited C)	A, B, C	A, B, C	A, B, (limited C)	A, B, C	K (limited B)
Extinguishing Mechanism	Oxygen displacement	Cooling, fuel wetting, radiant blocking	Cooling, steam generation, oxygen dilution	Heat absorption, flame inhibition	Oxygen displacement	Combined: Cooling + inerting /atomization	Flame inhibition, surface blanketing	Saponification, surface cooling
Residue	None	High	Minimal	None	None	None	Heavy, powder-based (corrosive)	Liquid film/residue
Agent Storage	High (bulk or multiple cylinders)	Moderate to large, pumps and tanks	Moderate (pressurized or pumped water)	Moderate (liquid under pressure)	High (multiple compressed gas cylinders)	High; (water tank and multiple compressed gas cylinders)	Bulk cylinder	Bulk cyclinder
Activation	Electronic or manual	Electronic (deluge or pre-action)	Electronic, thermal, or manual	Electronic, cross-zoned detection	Electronic, cross-zoned detection	Electronic cross-zoned detection or pneumatic	Fusible link or electronic	Fusible link or electronic
Speed of Discharge	Fast (≤10 s)	Moderate (≤30 s)	Fast (≤10 s)	Fast (≤10 s)	Moderate (≤60 s)	Fast (≤10 s)	Moderate (≤30 s)	Fast (≤10 s)

Criteria	CO_2 (High- and Low-pressure)	Water Spray/ Automatic Sprinklers	Water Mist	Clean Agents (FM-200, Novec 1230)	Inert Gas (IG-100, IG-55, IG-541)	Hybrid Systems	Dry Chemical	Wet Chemical
Time to Extinguishment	30 s	30 s to several mins	30 s to 120 s	10 s	60 s to 120 s	60 s to 180 s	10 s to 30 s	10 s to 30 s
Effectiveness in Enclosures	High	Moderate	High	High	High	High	Limited due to dispersion issues	Poor (conductive, residue)
Suitability for Generator Protection	Suitable (safety challenges)	Caution – flooding, damage risk	Highly suitable	Suitable	Suitable	Highly suitable	Unsuitable	Unsuitable
Electrical Compatibility	Excellent	Poor (large volume of water)	Good (non-conductive mist w/ deionized water)	Excellent	Excellent	Excellent; low volume, ultra-fine droplets	Poor- leaves corrosive residue	Poor- can damage electronics
Conductivity	Nonconductive	Conductive	Nonconductive	Nonconductive	Nonconductive	Nonconductive	Nonconductive agent, but messy	Conductive (aqueous)
Toxicity to Personnel	High (lethal at 17% vol; which is far below design concentrations)	None	None	Low to Moderate (concentration must remain below LOAEL)	Low (within exposure time limits)	Low (within exposure time limits)	Moderate (Irritating, potentially harmful)	Low to moderate
System Cost	Moderate	Low to Moderate	Moderate to High	High	High	High to Very High (advance detection systems typical)	Low	Low to Moderate

Criteria	CO_2 (High- and Low-pressure)	Water Spray/ Automatic Sprinklers	Water Mist	Clean Agents (FM-200, Novec 1230)	Inert Gas (IG-100, IG-55, IG-541)	Hybrid Systems	Dry Chemical	Wet Chemical
Maintenance Complexity	High (weighing, inspection)	Moderate	Moderate	Moderate	Moderate	Moderate to High	Moderate	Low to Moderate
Environmental Impact	Low (no ODP/GWP)	Low	Very low	FM-200: moderate GWP; Novec: very low	Very low	Very low	Neutral to low	Low Biodegradable
Design Flexibility	Total flood or local	Directional/ local only	Total flood or local	Total flood or local	Total flood or local	Total flood or local	Local application only	Local application only
NFPA Guidance	NFPA 12	NFPA 15	NFPA 750	NFPA 2001	NFPA 2001	NFPA 770	NFPA 17	NFPA 17A
Best Use Cases	Enclosed, unoccupied machinery rooms and spaces	Transformer decks, exposed or open machinery	Generators, turbines, enclosed spaces	Control rooms, electronics, archives	Archives, cleanrooms, sensitive enclosures	Mixed hazards, confined but ventilated spaces,	Industrial, electrical fires	Commercial kitchen fires

6.0 Conclusion

After conducting a detailed comparison of the different extinguishing agents, the hybrid fire extinguishing system shows the greatest potential to replace Reclamation's existing CO_2 extinguishing systems. This is primarily based on the extinguishing efficiency of the hybrid system by using two agents to extinguish flaming combustion and prevent reignition from smoldering combustion. The hybrid system does exact a higher upfront cost but the savings in ITM compared to CO_2 more than makes up for the difference. Additionally, hybrid systems are very safe and pose a low risk to personnel.

Other agents and systems are also good candidates for replacing CO_2 systems. Inert gas and water mist systems could also be used. These are the constituents of the hybrid but on their own could be very effective. Water mist would eliminate any potential health hazards. Inert gas systems could possibly swap out CO_2 with very little changes to the design and equipment greatly reducing instillation costs.

Clean agents like FM-200 and Novec 1230 were promising but due to the environmental concerns, increased regulations, and the phaseouts in domestic production, they are no longer a long-term option.

Water spray systems present to many complications for cleanup and water management. Additionally, shielding from the generator configuration can have a large impact on the effectiveness of the system. Though listed by FM Global as an option, these systems are not ideal for hydroelectric generators.

Dry and Wet chemical systems are not appropriate for generator protection. Dry chemicals may be not conductive, but they are corrosive and cleanup in intense. Wet chemicals are not designed for Class A solid fuels like the generator windings and just would not work.

7.0 Path Forward

More research is required to truly inform the designer and the end user as to which system is best for their facility. More data is needed to compare agent and system effectiveness inside the complex geometry of a hydroelectric generator. Test scenarios need to consider high voltage power and failures of protection systems. Winding materials also need to be considered as well as the possibilities of permitting self-extinguishment from newer winding materials and confirmation of fire prior to release. Application rates and agent quantities need to be ascertained through more experimentation.

8.0 References

Almont, Z. (2022, January). Stepping Beyond Standard to Enhanced Safety. *Water Power Magazine*, pp. 19-20. Retrieved from https://content.yudu.com/web/442ay/0A444q7/WPD0122-Pros/html/index.html?page=20&origin=reader

Alpert, R. L. (2008). Basics of Fire and Fire Science. In P. Arthur E. Cote (Ed.), *Fire Protection Handbook* (20th ed., pp. 2-1 thru 2-20). Quincy, Massachusetts, USA: National Fire Protection Association.

Arthurs, G., & Sudhakar, M. (2005). Carbon Dioxide Transport. *Continuing Education in Anaesthesia, Critical Care & Pain, 5*(6), 207-210. doi:10.1093/bjaceaccp/mki050

Babrauskas Ph.D., V. (2021). *Electrical Fires and Explosions.* New York, New York, USA: Fire Science Publishers.

Ballard, R., & Owens, S. (2015). Sticky Wickets: Finding the Best Fire Protection for Generators.

Blonk, H. C. (1941, December). *World's Largest Hydrogenerator Guarded Against Fire* (Vol. 31).

BOR. (1984). *CO2 Fire Protection Study for Hydrogenerators.* Denver,CO: Bureau of Reclamation.

BOR. (1984). *CO2 Fire Protection Study for Hydrogenerators.* Engineering and Research Center, Electrical Branch Division of Design. Denver,CO: Bureau of Reclamation.

BOR. (2005). *FIST 5-12, CO2 System Operation and Maintenace.* Bureau of Reclamation, Hydroelectric Research and Technical Services Group. Denver, CO: Bureau of Reclamation.

BOR. (2019). *FIST 1-1, Hazardous Energy Control Program.* Denver, Colorado: Bureau of Reclamation, Power Resource Office.

Braidech, M. M., Neale, J. A., & Durfour, R. E. (1955). *The Mechanism of Extinguishment of Fire by Finely Divided Water.* Underwriters Laboratories Inc. New York: National Board of Fire Underwriters.

Butler, J. P., & Tsuda, A. (2015, April 02). Transport of gases between the environment and alveoli - theorectical foundations. *HHS Public Acess*. Department of Health and Human Services.

Caldwell, C. A. (1997). Roxburgh Generator Water Mist Fire Protection. In *IPENZ Annual Conference 1997, Proceedings of: Engineering our nation's future; Volume 1; Papers presented in the technical programme of the IPENZ Annual Conference held in Wellington, February 7-10, 1997* (pp. 200-205). Wellington, New Zealand: Institution of Professional Engineers New Zealand.

Carbon Dioxide as a Fire Suppressant: Examing the Risks. (2000). United States Environmental Protection Agency.

Chiu, C.-W., & Li, Y.-H. (2015). Full-scale experimental and numerical analysis of water mist system for sheltered fire sources in wind generator compartment. *Process Safety and Environmental Protection, 98*, 40-49.

Conroy, M. T. (2017). *Fire Suppression Systems and Portable Fire Extinguishers.* Charlotte: National Fire Protection Association.

Consulting, A. X. (2020). *Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations.* Hartford: Property Risk Consulting Guidelines- AXA XL Risk Consulting.

Delcourt, D. (2006). *Technology Review: Fire Protection and Suppression in Hydroelectric Plants.* CEA Technologies Inc.

Dieken, D. (2009, April 1). *Fire Safety in Modern Hydroelectric Stations*. Retrieved from Power Magazine: https://www.powermag.com/fire-safety-in-modern-hydroelectric-stations/

Dieken, D. (2011, April 1). *Fire Protection Options for Air-Cooled Hydroelectric Generators*. Retrieved from POWER Magazine: https://www.powermag.com/fire-protection-options-for-air-cooled-hydroelectric-generators/

Dieken, D. (2011, April 1). *Fire Protection Options for Air-Cooled Hydroelectric Generators*. Retrieved from POWER Magazine: https://www.powermag.com/fire-protection-options-for-air-cooled-hydroelectric-generators/

Dieken, D. (2012, November 1). *Fire Suppression for Combustion Turbine in Enclosures*. Retrieved from Turbomachinery International: https://www.turbomachinerymag.com/view/fire-suppression-for-combustion-turbines-in-enclosures

DiNenno, P. J., & Forssell, E. W. (2016). Clean Agent Total Flooding Fire Extinguishing Systems. In M. Hurley, *SFPE Handbook of Fire Protection Engineering* (pp. 1483-1530). New York: Springer.

DOI. (2017). *Replacements, Units, Service Lives, Factors.* Bureau of Reclamation. U.S. Department of Army, U.S. Department of Energy, U.S. Department of the Interior.

(2020). *Fire Protection for Gas Turbines and Electric Generators.*

Fire Protection for Power Generation. (n.d.). Retrieved from Marioff: https://www.marioff.com/fire-protection/fire-protection-for-industry-and-energy/fire-protection-for-power-generation

Fire Ranger. (2019, Feb 11). *History of the Fire Extinguisher*. Retrieved from Fire Ranger: https://www.fireranger.com/history-of-the-fire-extinguisher/

FM Global. (2020). *Property Loss Prevention Data Sheets, 5-3 Hydroelectric Power.* Factory Mutual Insurance Company.

FM Global Group. (2012). *Approval Standard for Hybrid (Water and Inert Gas) Fire Extinguishing Systems* (Vol. Class Number 5580). FM Approvals LLC.

FST. (n.d.). *Modular pre-engineered systems: Inert gas*. Retrieved from Fire and Security Techniques: https://fst.co.za/fire-suppression-systems/modular-pre-engineered-systems/inert-gas/

Gameiro, V. M. (1993). *Fine Water Spray Fire Suppression Alternative to Halon 1301 in Gas Turbine Enclosures.* Montreal, Quebec.

Gard AS. (2012). Fixed CO2 Fire-Extinguishing Systems- Consequences of Delayed Release. *Loss Prevention Circular*(No. 06-12).

(2009). *Generator Maintenance, Inspection, and Test Programmes.*

Glockling, J. L., Edwards, M., & Watkins, S. (2001). Development of a Low-Pressure Fine Water Spray Fire Suppression. *Halon Options Technical Working Conference 24-26 April 2001*, (pp. 414-424).

Hall, Ph.D., J. R. (2006). *An Analysis of Automatic Sprinkler System Reliability Using Current Data.* National Fire Portection Agency.

Hansen, R., Ishiyama, M., Senecal, J. A., Willms, C. F., Wysocki, T., & Young, R. (2000). *Carbon Dioxide as a Fire Suppressant: Examining the Risks.* Washington: United States Environmental Protection Agency.

Harrington, J., & Senecal, J. A. (2016). Carbon Dioxide Systems. In M. Hurley, *SFPE Handbook of Fire Protection Engineering* (pp. 1531-1586). New York: Springer.

International Code Council. (2017). *2018 International Fire Code.* Country Club Hills, IL: ICC Publications.

Kaiser, L. (2017, December 19). *The Origional Clean Agent: Carbon Dioxide Systems*. Retrieved from ORR Protection: https://www.orrprotection.com/mcfp/original-clean-agent-co2-systems

Kidde. (2025). *Kidde*. Retrieved March 18, 2025, from https://www.kidde.com/home-safety/en/us/about/history/

Kim, A. (2002). Overview of recent progress in fire suppression technology. *Invited Keynote Lecture at the 2nd NRIFD Symposium, Proceedings, Tokyo, Japan, July 17-19, 2002*, (pp. 1-13). Tokyo, Japan.

Kirschbaum, D. J. (2017). *Powerhouse Fire Detection and Suppression Design Basis Memorandum for Replacement of CO2 Systems.* Seattle City Light.

Liu, Y., Xue, Q., Zuo, H., Yang, F., Peng, X., & Wang, J. (2021). Effects of CO2 and N2 Dilution on the Combustion Characteristics of H2/CO Mixture in a Turbulent, Partially Premixed Burner. *ACS Omega* , pp. 15651-15662.

Liu, Z., & Kim, A. K. (1999). A Review of Water Mist Fire Suppression Systems—Fundamental Studies. *Journal of Fire Protection Engineering, 10*(3), 32-50.

Madrzykowski, D., & Stroup, D. W. (2008). Flammability Hazard of Materials. In A. E. Cote (Ed.), *Fire Protection Handbook* (pp. 2-31 - 2-48). Quincy, Massachusetts: National Fire Protection Agency.

Mawhiney, J. R., & Back III, G. G. (2016). Water Mist Fire Suppression Systems. In *SFPE Handbook of Fire Protction Engineering* (pp. 1587 - 1645). New York: Springer.

McGree, T. (2023). *Fire in Industrial or Manufacturing Properties.* Quincy: NFPA Research.

National Hydropower Association, O. E. (2017). *Unexpected Activation of CO2.* Retrieved May 14, 2022, from https://hydroexcellence.org

NFPA 12: Standard on Carbon Dioxide Extinguishing Systems. (2018). Quincy, MA: National Fire Protection Association.

NFPA 13, Standard for the Installation of Sprinkler Systems. (2019). Quincy, MA: National Fire Protection Association.

NFPA 15, Standard for Water Spray Fixed Systems for Fire Protection. (2017). Quincy, MA: National Fire Protection Association.

NFPA 750-Water Mist Fire Protection Systems. (2019). Quincy, MA, United States: National Fire Protection Association. Retrieved August 01, 2025, from https://link.nfpa.org/free-access/publications/750/2019

NFPA 850: Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations. (2020). Quincy: National Fire Protection Association.

NUREG/CR-6850. (2005). *EPRI/NRC-RES Fire PRA Methodology for Nuclear Power Facilities.*

Osburn, G. (2005). *Facilities, Instructions, Standards, and Techniques Volume 5-12: CO2 System Operation and Maintenance.* Denver: U.S. Department of the Interior Bureau of Reclamation.

Puchovsky, M., & Homeister, C. (2016). Engineering Considerations for Fire Protection System Selection. In M. Hurley, *SFPE Handbook of Fire Protection Engineering* (pp. 1289-1313). New York: Springer.

Quality, O. o. (n.d.). *U.S. Department of State*. Retrieved 07 12, 2025, from https://www.state.gov/the-montreal-protocol-on-substances-that-deplete-the-ozone-layer

Raia, P., & Gollner, M. J. (2014). *Literature Review on Hybrid Fire Suppression Systems.* Fire Protection Research Foundation. Retrieved from www.nfpa.org/foundation

Reilly, W. (2008). Dual Agent Extinguishing System: Victaulic Vortex. *Prepared for Presentation at American Institute of Chemical Engineers 2008 Spring National Meeting 42nd Annual Loss Prevention Symposium New Orleans, La April 7-9, 2008*, (pp. 1-6). New Orleans, Louisiana.

Rein, G. (2016). Smoldering Combustion. In M. Hurley (Ed.), *SFPE Handbook of Fire Protection Engineering.* Society of Fire Protection Engineers.

Roberts, L. (2012, August 16). *Barkley hydropower rehabilitation gets a 270-ton lift.* Retrieved 2024, from US Army Corps of Engineers Nashville District Website: https://www.lrn.usace.army.mil/Media/News-Stories/Article/493417/barkley-hydropower-rehabilitation-gets-a-270-ton-lift/

Santangelo, P. E., & Tartarini, P. (2010). Fire Control and Suppression by Water-Mist Systems. *The Open Thermodynamics Journal, 4*, 167-184.

Sardqvist, S. (2002). *Water and Other Extinguishing Agents.* (A.-L. Goransson, Ed.) NRS Tryckeri AB.

Seymour, R. N. (2012). *Automate Generator Deluge Systems on Units 5 and 6, Bay d'Espoir Hydroelectric Generator Station.* Newoundland Labrador Hydro.

Tatem, P. A. (1994). *A Review of Water Mist Technology for Fire Suppression.* Washington: Navel Research Laboratory.

Twin-Fluid Hybrid Fire Suppression Explained. (n.d.). Retrieved April 12, 2023, from Fire and Safety Security of India: https://firesafetysecurityindia.com/twin-fluid-hybrid-fire-suppression-explained/

USACE. (2023). Phase 3 Study Generator Fire Suppression Meeting.

Victaulic. (n.d.). *Victaulic Vortex™ hybrid fire extinguishing system*. Retrieved from https://www.victaulic.com/systems/victaulic-vortex-hybrid-fire-extinguishing-system/

Wickham, P.E., R. T. (2003). *Review of the Use of Carbon Dioxide Total Flooding Fire Extinguishing Systems.* New Hampshire: Wicham Associates.

Wierenga, P. H., & Holland, G. F. (1999). Developments In and Implementation of Gas Generators for Fire Suppression. *Halon Options Technical Working Conference.* Redmond: Primex Aerospace Company.

Wyscocki, T. J. (2017). Carbon Dioxide and Application Systems. In A. E. Cote (Ed.), *Fire Protection Handbook* (Twentieth ed., pp. 17-1). Quincy, Massachusetts, USA: National Fire Protection Association.

Yu, H.-Z., & Newman, J. S. (2008). Theory of Fire Extinguishment. In A. E. Cote (Ed.), *Fire Protection Handbook* (12th ed., Vol. 1, pp. 2-79 through 2-92). Quincy, Massachusetts: National Fire Protection Association.