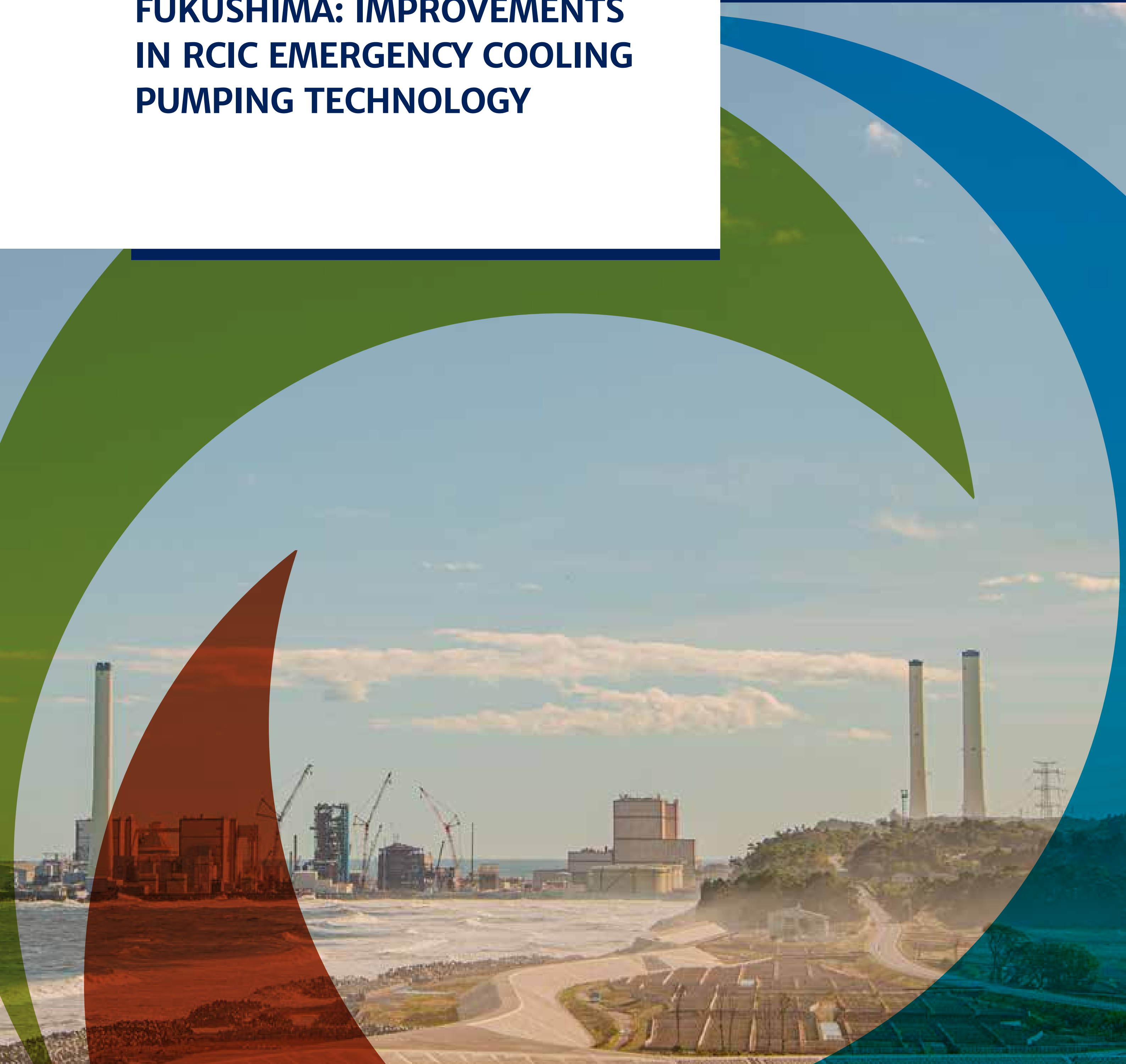
CELEROS FLOW TECHNOLOGY

WHITEPAPER

LEARNING THE LESSONS OF FUKUSHIMA: IMPROVEMENTS IN RCIC EMERGENCY COOLING PUMPING TECHNOLOGY

CLYDEUNION® PUMPS



ABOUT CELEROS FLOW TECHNOLOGY

Celeros Flow Technology (Celeros FT) represents a major force in flow control technology, concentrating on serving key market sectors where its solutions will have maximum impact. These are Oil & Gas, Power (nuclear, conventional and renewable), Chemical Processing, Energy Transition, Water Treatment and Marine/Defence. Thanks to continued engineering investment, and by always looking to take an innovative approach to the challenges faced, the company's solutions set industry benchmarks in terms of their performance and reliability.

Celeros FT brands include ClydeUnion Pumps, Copes Vulcan, M&J Valve, GD Engineering, Plenty and S&N Pumps. Each is a recognized and well-respected leader in its particular field.

The company's involvement in the nuclear power market began with the first ever industrial scale nuclear power plant and continues with nuclear class 1, 2 and 3 pump and valve installations in more than 65% of operational nuclear power plants worldwide. In addition to our involvement in the commercial nuclear power market, we continue to provide pumping solutions to the world's naval nuclear fleets, research reactors and other nuclear facilities. Our market focused research and development programs ensure that our solutions match the demanding requirements of current and future technologies, such as generation IV, fusion and small modular reactors.

ABBREVIATIONS

ABWR	Advanced Boiling Water Reactor
AERB	Atomic Energy Regulatory Board
AFW	Auxiliary Feedwater
BWR	Boiling Water Reactor
CUP	ClydeUnion Pumps, a Celeros Flow Technology brand
FNAAR	Fukushima Nuclear Accident Analysis Report
HPCI	High Pressure Core Injection
IAEA	International Atomic Energy Agency
IC	Isolation Condensers
INES	International Nuclear and Radiological Event Scale
IPCC	Intergovernmental Panel on Climate Change
ISLOCA	Interfacing systems loss of coolant accident
LEU	Low Enriched Uranium
MOX	Mixed-Oxide
NISA	Nuclear and Industrial Safety Agency
OEM	Original Equipment Manufacturers
PWR	Pressurized Water Reactor
RCIC	Reactor Core Isolation Cooling
SBO	Station Blackout
TEPCO	Tokyo Electric Power Company, Inc.
TWL™	Turbine Water Lubricated pump

1.0 INTRODUCTION

Scientists and policy makers are in broad agreement that low carbon nuclear power is an important part of the transition to clean energy. Indeed, it is widely believed that swiftly scaling up nuclear power capacity could address not only the challenges of climate change but could also tackle energy poverty and promote economic development.

Although technology-neutral organizations such as the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) recognize nuclear power's ability to address major global energy challenges, public confidence in the safety of nuclear power plants is less certain. There have been only two major reactor accidents in the history of civil nuclear power – Chernobyl and Fukushima Daiichi – during 18,500 cumulative reactor-years of commercial nuclear power operation in 36 countries[1]. However, the repercussions of such incidents are still influencing public perceptions about nuclear power. It is therefore essential that the nuclear power sector can demonstrate how much safer the technology is today.

According to the World Nuclear Association, the Chernobyl accident in 1986 was the result of a flawed reactor design combined with inadequately trained personnel. The resulting steam explosion and fires released around five percent of the radioactive reactor core into the environment and deposited radioactive materials over parts of Europe[2].

By contrast, the earthquake and subsequent tsunami that hit the coast of Japan on the afternoon of March 11, 2011 was a natural disaster that triggered a series of catastrophic events at the Fukushima Daiichi nuclear plant. The sequence of events that led to the failure of the reactor cooling systems and the subsequent explosion have been examined in detail by nuclear regulatory bodies and the scientific community so that lessons can be learned to improve legislation and safety processes. Arguably, less attention has been paid to the performance of the physical equipment and the role that engineering can play in improving safe operation.

In this whitepaper, Celeros FT focuses on the engineering aspects of the Fukushima incident and explores what practical solutions have been developed since. In particular, it examines the role of pumping equipment in the reactor core isolation cooling (RCIC) system and the steps that have been taken to improve this technology. In addition to boiling water reactors (BWR), the final pump design is also appropriate for pressurized water reactors (PWR) serving as an auxiliary feedwater pump.

2.0 THE SEQUENCE OF EVENTS

A severe seismic event occurred on 11 March 2011 at 14.46 (local time) off the Japanese coast near Honshu Island, approximately 250 miles north of Tokyo. With a magnitude of M9.0, the Tohoku-Chihou-Taiheiyo-Oki earthquake was the largest ever observed in Japan and the fourth largest recorded earthquake in the world. The Great East Japan Earthquake, as it came to be known, also triggered a tsunami that flooded more than 200 square miles of coastal land.

In combination, these events sparked a humanitarian disaster in north eastern Japan. More than 20,000 people were reported dead or missing and approximately 500,000 were displaced. The direct economic impacts and damage to physical infrastructure exceeded $360 billion[3].

The earthquake and tsunami also initiated a severe nuclear accident at the Fukushima Daiichi Nuclear Power Station, operated by the Tokyo Electric Power Company (TEPCO).

2.1 NUCLEAR ACCIDENT

Unusually, the Great East Japan Earthquake was caused by joint movement in several seismic source regions. Previous earthquake and tsunami incidents were caused by a single source – and this was the design basis for considering the magnitude of ground movement and height of tsunami waves in relation to nuclear power station design at the time[4].

Fukushima nuclear power station was no exception. It was the first nuclear power station to be designed and constructed entirely by TEPCO. The first unit at the site was commissioned in 1971. In total, the station has six boiling water reactors (BWR), which together have a power generation capacity of 4.69GW. Units 1 to 5 are Mark I type while Unit 6 is a Mark II built with containment structures. All the reactors except Unit 3 continued using low enriched uranium (LEU). Unit 3 was fed with mixed-oxide (MOX) fuel since September 2010[5].

The Great East Japan earthquake stretched from offshore of Iwate prefecture to Ibaraki prefecture in Japan and a number of nuclear power stations lay in its path. Eleven reactors across the affected sites responded to the incident as designed, by going into automatic shutdown. Among them were Units 1, 2 & 3 at Fukushima Daiichi, which were in operation at the time of this event. Units 4, 5 & 6 had been shut down for regular inspection and maintenance purposes when the earthquake struck.

Immediately after the earthquake, offsite power was lost to all three units in operation at the power station, leading to automatic start-up of emergency diesel generators. Approximately 40 minutes later the tsunami struck. Waves measuring in excess of 14m high hit the site and flooded the power station. This caused the shutdown of emergency diesel generators at 15.41, leading to station black out (SBO). This meant that the plant had to rely upon batteries and diesel-driven pumps.

Despite the emergency diesel generators and battery backups, the cooling supply was lost to Unit 1 within several hours of the earthquake-tsunami event. Similarly, Unit 2 lost cooling after 71 hours and Unit 3 lost cooling after 36 hours, leading to hydrogen build-up and subsequent explosions in all the units[6]. This represented an unprecedented nuclear event and was rated as a Level 7 "Major Accident" on the International Nuclear and Radiological Event Scale (INES) on 12 April 2011[7].

3.0 GLOBAL REPERCUSSIONS

The scale of the accident at Fukushima prompted an unprecedented response from nuclear regulatory bodies around the world. There was an urgent need to understand how and why the chain of natural events had led to such a catastrophic failure, and whether this type of incident could occur elsewhere.

The International Atomic Energy Authority (IAEA), which counts more than 160 countries among its members, played a prominent role in co-ordinating these investigations. It drew several conclusions, including regulatory, design and emergency response failures[8].

The IAEA report found that a major contributing factor to the Fukushima accident was the widespread assumption that Japan's nuclear power plants were so safe that an incident of this magnitude was simply unthinkable. This assumption had not been questioned by nuclear power plant operators and was not challenged by regulators or by the Government. As a result, Japan was not sufficiently prepared for a severe nuclear accident in March 2011. In addition, the report highlighted that responsibilities were divided among multiple organisations, and it was not always clear where authority lay.

Emergency preparedness and response management, as well as procedures for planning for the management of a severe accident, had to be completely updated as an outcome of the Fukushima incident. There were also certain weaknesses in plant design to address. Chief among these was the assumption that there would never be an interruption in electrical power at a nuclear power plant for more than a short period. The possibility of several reactors at the same facility suffering a crisis at the same time was not even considered. This was compounded by the fact that insufficient provision was made for the possibility of a nuclear accident occurring at the same time as a major natural disaster.

Many of the conclusions that came out of the investigation were by no means unique to Japan. Consequently, other countries responded to the accident with measures that included carrying out 'stress tests' to reassess the design of nuclear power plants against site-specific extreme natural hazards, installing additional backup sources of electrical power and supplies of water, and strengthening the protection of plants against extreme external events, including terrorist attack.

4.0 THE ENGINEERING CONSEQUENCES

Let us now examine the engineering consequences of the incident. After the loss of AC power (due to earthquake) and DC power (due to tsunami), the Unit 1 cooling system and High Pressure Core Injection (HPCI) system at Fukushima Daiichi became inoperable. Although it continued to function for a couple more days, the Reactor Core Isolation Cooling (RCIC) system in Unit 2 also became inoperable. In Unit 3 the DC power was not lost immediately and the core cooling was performed either by RCIC or HPCI. However, the DC power eventually became depleted and the cooling function was lost in less than two days (NISA, 2012). A chronology of important events at all three Units until explosion is given in Appendix 2.

The DC power system supplies power to critical equipment and devices like HPCI, RCIC, Isolation Condensers (IC) and various other instrumentation and control devices. Hence the availability of the emergency power supply in case of reactor shutdown is crucial. At Fukushima, the system failed with catastrophic results.

This led the Nuclear and Industrial Safety Agency (NISA) to recommend that:

- The availability of necessary electrical equipment to distribute electricity to emergency devices must be assured.
- The emergency DC power supply must be available immediately after reactor shutdown to prevent and control the progression of a subsequent accident.
- Operators must facilitate alternative power supply from outside the plant, such as mobile power[9].

4.1 ESSENTIAL RELATIONSHIP BETWEEN POWER AND COOLING

All the reactors at Fukushima stopped operation automatically when the earthquake motion was detected. This in turn led to the stoppage of the main feed water pumps, as follows:

- Unit 1 lost all AC power and emergency DC power almost immediately, due to incursion of the tsunami. This made the cooling systems (IC, HPCI) redundant, since they could not be operated without power.
- In Unit 2, as the pressure inside the reactors increased, the steam was vented and RCIC was manually started to maintain the reactor water level. In the absence of HPCI due to loss of DC power, RCIC continued operate until around 13.00 hours on 14 March.
- In Unit 3, water was injected by the RCIC system which was started manually and continued to function until 11.36 on 12 March 2011. It is assumed that there was limited DC power availability. As a result, the HPCI system started automatically after the stoppage of RCIC but stopped at 02.42 on 13 March.

In other words, water injection to cool the reactor core ceased for 14 hours, 9 minutes in Unit 1; 6 hours, 29 minutes in Unit 2; and 6 hours, 43 minutes in Unit 3. Failure of the water injection system over these extended periods was a key reason why the Fukushima accident developed to a point where explosion was inevitable. This sequence of events emphasises the importance of the relationship between power supply and cooling systems.

5.0 THE ROLE OF PUMPING EQUIPMENT IN NUCLEAR ENVIRONMENTS

The role of flow control equipment in the safe operation of nuclear power stations cannot be underestimated (See Appendix 1). Pumps form one of the most critical elements in a nuclear plant. Large-capacity pumps and high-pressure pumps used in domestic PWR nuclear power plants include reactor (primary) coolant pumps, charging pumps with safety functions, safety injection pumps and residual heat removal pumps in the nuclear island, as well as main feedwater pumps, condensate pumps and circulating water pumps in the turbine island.

Pumps fit for use in nuclear applications are classified by ASME into three different categories, depending on their purpose:

- Class 1: pumps operating inside the reactor main coolant pressure boundary.
- Class 2: pumps that are not part of the reactor main coolant pressure boundary, but are important for shutdown, emergency core cooling, post-accident containment heat removal and post-accident fission product removal.
- Class 3: Those not in Class 1 and Class 2, but which are required for cooling water, post-accident atmospheric clean up and seal water systems important to safety.

The most safety-significant systems in the case of a SBO are the RCI systems for BWRs and the auxiliary feedwater (AFW) system for PWRs. The steam-driven water pump in these systems is typically the frontline component that addresses SBO and provides core heat removal.

Proper operation of the AFW system in a PWR traditionally requires DC power from a station battery, steam from the steam generators and an adequate supply of secondary plant water. The total amount of current draw on the station battery can be a limiting factor in determining the duration of SBO coping.

The preliminary investigations and subsequent reports following the Fukushima incident considered several pumping solutions.

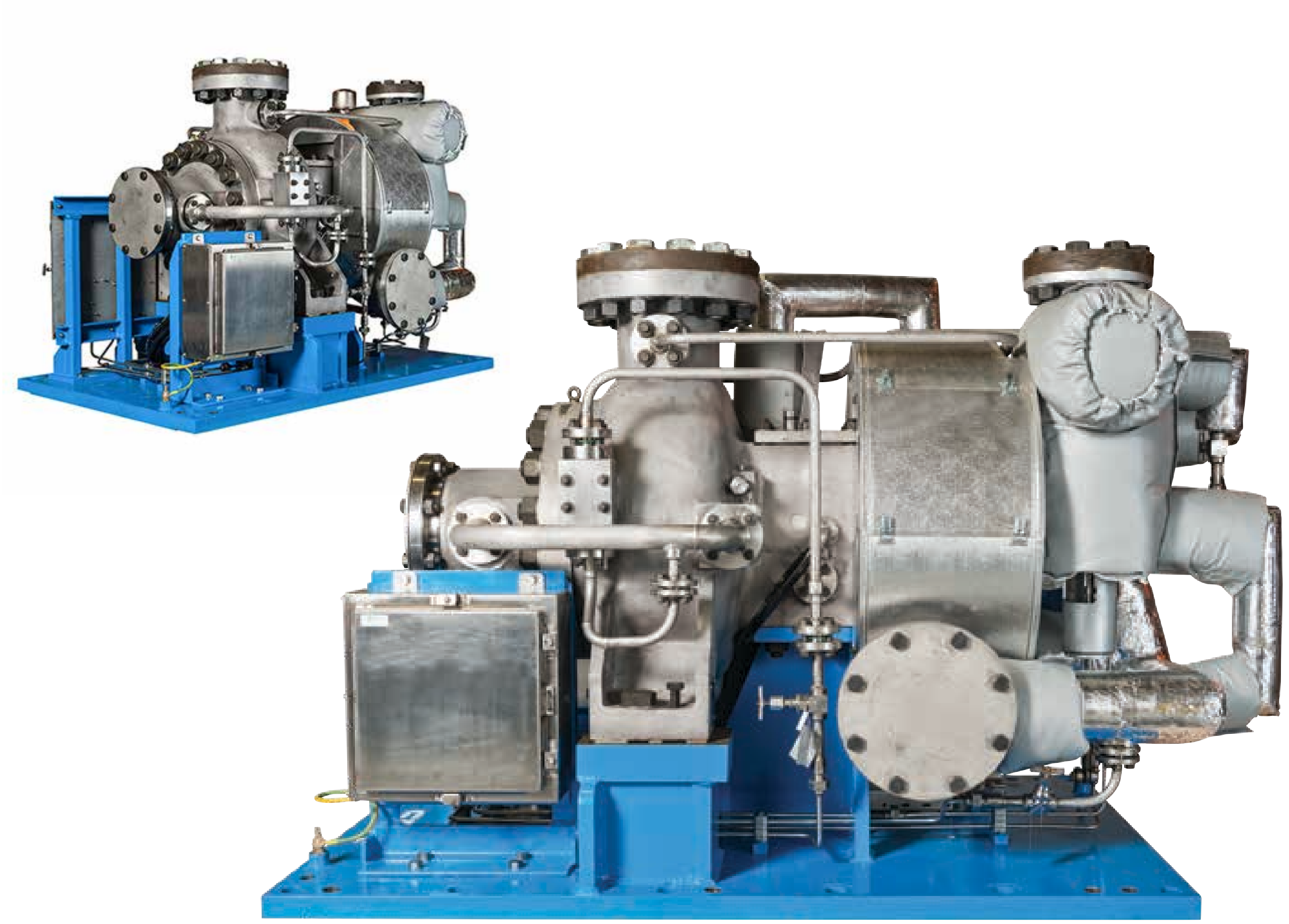
Celeros FT brand ClydeUnion Pumps (CUP) has concentrated its efforts on improving the unique design of its TWL™ pump set for RCIC applications. In addition, it has worked with Westinghouse to incorporate such turbine/pump sets to provide an improved plant AFW system that addresses many of the concerns raised by the Fukushima accident[10].

5.1 THE CASE FOR DEPLOYING TWL™ PUMPS

The potential for TWL™ pump technology to improve reliability in nuclear power applications was being investigated even before the events at Fukushima. In the US, General Engineering proposed changes to the Design Control Document for advanced boiling water reactors (ABWR) as early as 2006, based on the following reasons:

- All RCIC system nuclear safety performance criteria continue to be met.
- All safety-related pressure boundary components now are ASME N-stamped.
- Reduced amount of piping subject to design pressure uprating due to ISLOCA (Interfacing System Loss Of Cooling Accident).
- Reduced RCIC pump room combustible fire loading due to elimination of lubricating oil.
- Elimination of potential radioactive bypass leakage path due to elimination of turbine shaft seals.
- Reduced number of active safety-related components (steam bypass valve, electronic governor, flow transmitter).
- Elimination of a potential dilution path for inerted primary containment atmosphere with deletion of the barometric condenser and its return line to the suppression pool.
- Reduced safety-related battery drain from reduced DC power demand during SBO scenarios with elimination of the bypass startup MOV and electronic flow controls and instruments[11].

TWL™ - TURBINE WATER LUBRICATED PUMP



5.2 TECHNOLOGY IMPROVEMENTS

The unique CUP TWL™ pump is a single wheel steam turbine, two-stage pump designed to ASME III Class 2 & 3 requirements. Both the turbine and impellers are mounted on a rigid shaft, supported by a central bearing assembly integral within a monobloc turbine/pump casing. It is one-third to one-half the size of a conventional pump and turbine unit, which makes it ideal for congested nuclear islands where space is at a premium. This compact proven design will also withstand water slugs in the steam line.

In the 1960s, the TWL™ concept was presented through the Institution of Mechanical Engineers. Originally designed for continuous operation as a feed pump for naval applications, the TWL™ went through a number of design changes and enhancements and has been an excellent solution for turbine-driven safety related duties in nuclear power plants since 1971, with more than one hundred installations to date.

The CUP TWL™ pump provides required performance pertaining to discharge head, flow rates and required steam conditions. It has a capacity of up to $350m^3$/hr (1550 USgpm) and a delivery up to 1300m (4265 ft). This pump therefore exceeds existing PWR installation requirements (1,200 psig and 900+ gpm), and the set is extendable for power uprates.

These pumps are designed in such a way that they require no external lubrication, no external cooling water, no drive coupling, no barometric tank or vacuum pump and – more importantly – no electrical connections. These units also incorporate self-contained turbine governor/controls and overspeed trip mechanisms within one package.

However, the main feature of the CUP TWL™ pump in the context of improved nuclear safety post-Fukushima is its extended coping capability under SBO conditions without supporting services (AC or DC supply). Even the control at partial flow is much simpler, since there is no need for repeated operator intervention to adjust the flow. This saves precious time and enables personnel to concentrate on other essential items in the event of a SBO or other incident.

5.3 SUBMERGENCE TESTED FOR COMPLETE PEACE OF MIND

The TWL™ has a single casing designed with no shaft protrusions, enabling it to start and operate while fully submerged. Extensive testing at CUP's Glasgow facility has shown that it will maintain safety performance and continue to operate with no adverse effects or detrimental changes to performance for a minimum of eight hours. During this time, the pump can be started and stopped, again with no detriments to its performance[12].

"Flow control functions that are self-adjusting and self-contained within the integrated turbine-pump increase operational reliability since there are no external control components or software required that could be a source of trouble for proper operations."

(Hisajima-Toshiba, 2010)[13]

6.0 CONCLUSION

A decade on from the Fukushima accident, power plant owners, operators, original equipment manufacturers (OEM), designers and regulators are acutely aware of the potential plant vulnerabilities that can lead to a complete loss of a unit's electrical power. The industry now recognizes that not only multiple natural phenomena but also terrorist/security challenges and even random equipment failure can initiate long periods of station black out[13].

RCIC pumping applications in the new generation ABWRs are part of emergency core cooling systems and provide essential decay heat removal to cope with SBO incidents. For this reason, highly reliable equipment with least margin for redundancy, and which can act on its own intelligence during an evolving situation, becomes mandatory.

The relationship between cooling systems and the availability of un-interrupted power supply in case of SBO should be of primary importance to nuclear power plant design and operation. The extended coping during SBO in the absence of any power supply and with very little or no monitoring makest the CUP TWL™ pump an extremely reliable solution for both existing and new sites. Approximately 100 TWL™ pumps have already been deployed to improve the safety and integrity of nuclear plants around the world.

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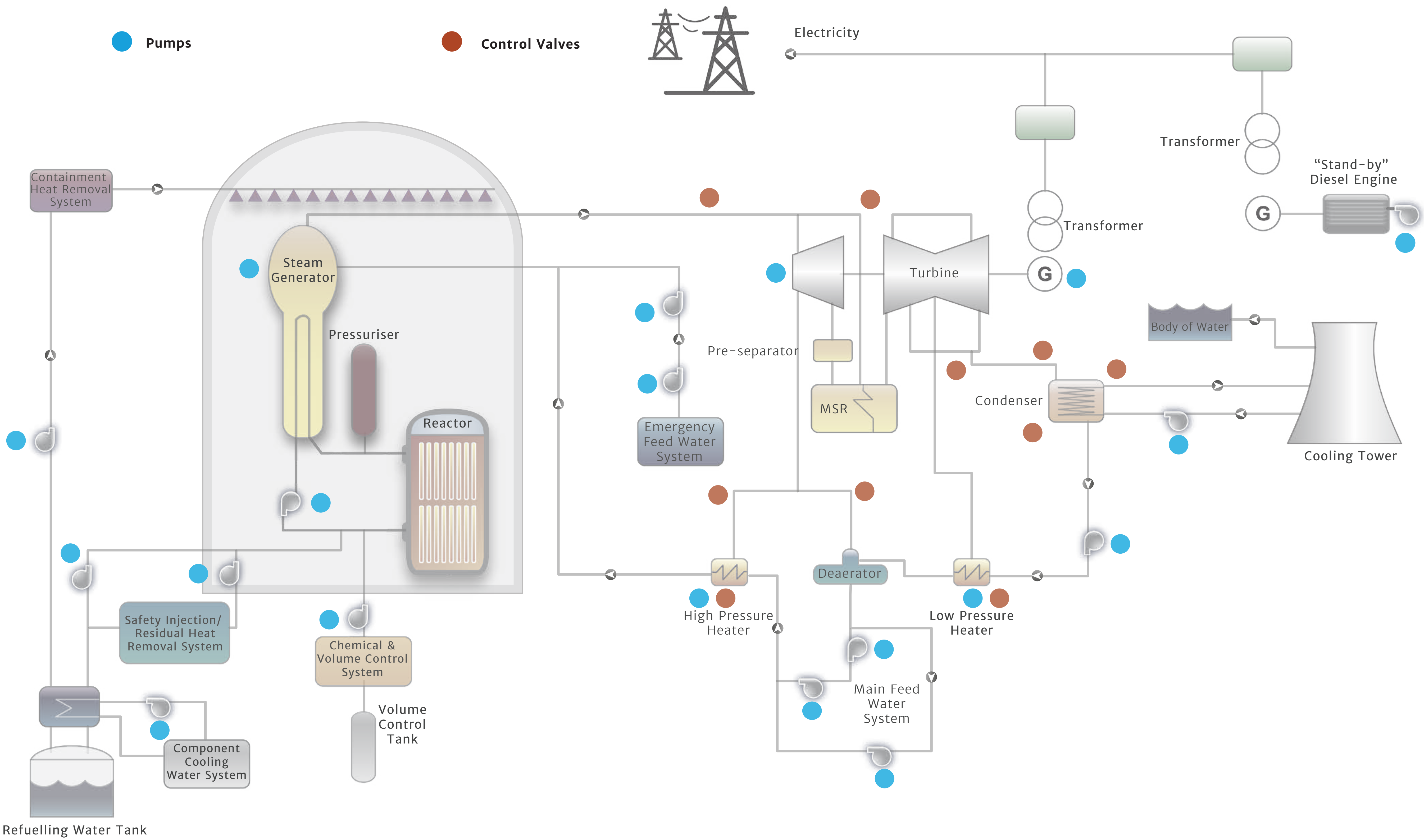
APPENDIX 1

COMPREHENSIVE CAPABILITY FOR ALL NUCLEAR PUMPS & CONTROL VALVES



APPENDIX 2

2.1 PROGRESSION OF EVENTS IN FUKUSHIMA DAIICHI UNIT 1

DATE / TIME	MAJOR PHENOMENA
11 MARCH 2011 14:46	**Earthquake Occurred** • Reactor shutdown automatically • External power supply lost • Emergency diesel generators activated
14:52	Isolation condensers automatically activated (subsequently valves opened and closed manually)
15:37	**Tsunami Arrived** • Seawater cooling system function lost • Emergency diesel generators shutdown • DC power supply (batteries, etc.,) shutdown • Isolation condenser function lost (meltdown)
~ 17:00	• Fuel rods exposed (assumed) • Core melted (assumed)
12 MARCH 2011 05:46	Freshwater injection by firefighting pumps
14:30	Vent (lowering of PVC pressure)
15:56	Explosion, thought to be hydrogen explosion, in reactor building
19:04	Seawater injection

Source: NISA, 2012

2.2 PROGRESSION OF EVENTS IN FUKUSHIMA DAIICHI UNIT 2

DATE / TIME	MAJOR PHENOMENA
11 MARCH 2011 14:47	**Earthquake Occurred** • Reactor shutdown automatically • External power supply lost • Emergency diesel generators activated
14:50	Reactor Core Isolation Cooling system (RCIC) activated
15:41	**Tsunami Arrived** • Seawater cooling system function lost • Emergency diesel generators shutdown • DC power supply (batteries, etc.,) shutdown
13-MARCH-2011 ~ 11:00	Vent (did not achieve lowering of PVC pressure)
14-MARCH-2011 13:25	Reactor Core Isolation Cooling System (RCIC) shutdown (assumed)
~ 18:00	Reactor pressure lowered (safety relief valve operation) • Fuel rods exposed • Core meltdown (assumed)
19:54	Freshwater injection by firefighting pumps
15 MARCH 2011 ~ 6:10	Sound of impact heard

Source: NISA, 2012

2.3 PROGRESSION OF EVENTS IN FUKUSHIMA DAIICHI UNIT 3

DATE / TIME	MAJOR PHENOMENA
11 MARCH 2011 14:47	**Earthquake Occurred** • Reactor shutdown automatically • External power supply lost • Emergency diesel generators activated
14:50	Reactor Core Isolation Cooling system (RCIC) activated
15:41	**Tsunami Arrived** • Seawater cooling system function lost • Emergency diesel generators shutdown
12 MARCH 2011 11:36	Reactor Core Isolation Cooling system (RCIC) shutdown
12:35	High Pressure Coolant Injection (HPCI) system activated automatically
13 MARCH 2011 02:42	High Pressure Coolant Injection (HPCI) shutdown
~ 08:00	• Fuel rods exposed (assumed) • Core melted (assumed)
~ 08:41 to 09:20	Vent (lowering of PVC pressure)
09:25	Seawater injection by firefighting teams
14 MARCH 2011 ~ 11:01	Explosion, thought to be hydrogen explosion in reactor building

Source: NISA, 2012

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