

## RELIABILITY OF THERMOELECTRIC COOLING SYSTEMS

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### ABSTRACT

A 10 year reliability study, on three types of laboratory equipments cooled by thermoelectrics is presented with a failure diagnosis.

The reliability of thermoelectric cooling systems is examined. These include small systems of a few tens of mm<sup>3</sup> with mW of cooling to large systems with volumes of m<sup>3</sup> and cooling powers of tens of kW.

The main entity of a thermoelectric system is the thermoelectric structure that consists of the thermoelectric material and the components that transfer heat. The mechanisms of performance degradation or failure of the thermoelectric structure are examined in detail. In addition to the structure the other entities are the auxiliary equipments: power supply, controls, fans and pumps; their reliability is examined from the point of view of the overall system reliability.

### INTRODUCTION

Companies using thermoelectrics for cooling were contacted about their experience on the reliability of their equipments, only one responded with documented data: Komatsu Electronics Inc. Japan. Their study is presented below because it reflects the reliability of equipments that are manufactured in series.

The reliability of a system depends on the quality of the development work and on manufacturing expertise. Difficulties arise because some systems are only built once or twice and therefore design, manufacturing and operating deficiencies have not been identified. In small systems little innovation is necessary in the structure, then the problems are generally in the auxiliaries. In big systems the problems are in the thermoelectric structure where there is innovation.

### RELIABILITY STUDY ON LABORATORY EQUIPMENTS

The quality assurance division of Komatsu Electronics Inc followed over a ten year period, starting in 1978, three of their marketed thermoelectric laboratory cooling equipments comprising 18 000 units in all. These equipments had been commercialized already for five years before the start of the study.

#### Description of the equipments

- Gas dehumidifier (for infrared gas analyser): 10 000 units
- Constant temperature liquid circulator: 5000 units
- 0° C Reference bath: 3 000 units

Figure 1 is a photograph of the gas dehumidifier. The gas to be dehumidified enters and exits at the top. The heat is evacuated into the ambient air through the fan that can be seen on the front panel.

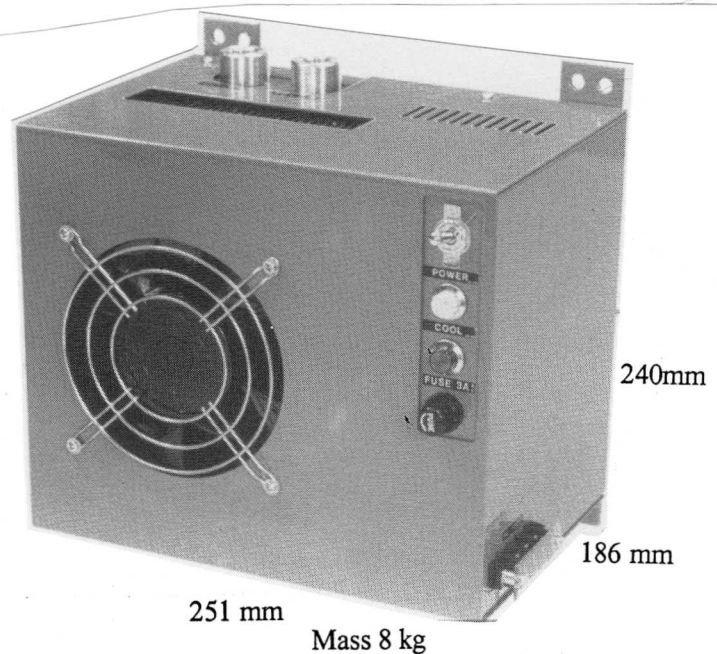


Figure 1 Gas dehumidifier

Figure 2 is a schematic of the circulator, which shows all the components of this equipment.

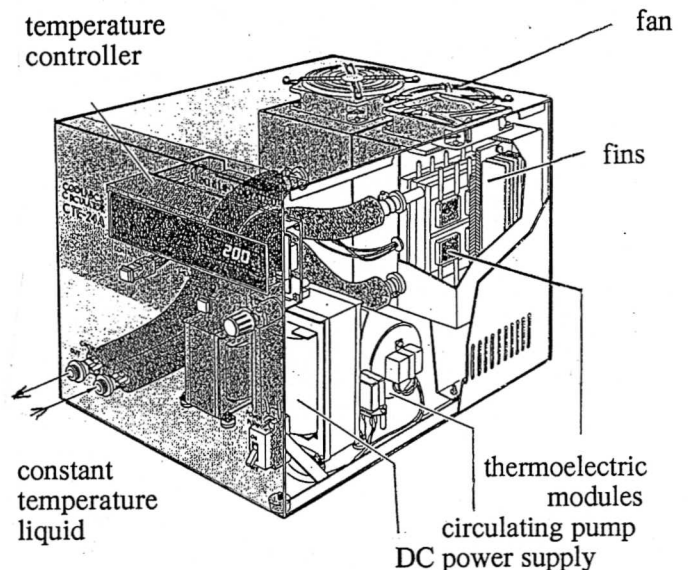


Figure 2 Constant temperature liquid circulator

### Repairs

When the client encountered problems, the units were repaired either on site or in their factory. The quality assurance division documented all repairs on 18 000 units in service. Over the 10 year period, 106 units were repaired.

The parts repaired were:

Thermoelectric structure	3 %
Power supplies	10 %
Control systems	52 %
Fans and pumps	35 %

## Analysis of this study

This study reveals:

- 1) The faulty equipments known to the manufacturer represented only 0.6 % of the units sold over a 10 year period indicating overall high reliability of these laboratory equipments.
- 2) Only 3 % of the repairs are on the thermoelectric structure. Thus structural breakdowns were minimal.

The Komatsu data on small systems corresponds to the authors own experience in the area of large systems in the range of tens of kW of cooling. A passenger railway coach with a thermoelectric air conditioning unit was built by Air Industrie in the late 1970's<sup>1</sup>. The system had a modified standard power supply for the high to low voltage AC converter and a prototype laboratory built DC converter and control system. It has operated for over 10 years, accumulating over 40 000 hours of operation. During this time there was no repair on the thermoelectric structure but the repairs on the control system and the power supply are estimated at well over 50. The auxiliaries were not specifically developed and industrially tested because the object was only to check the reliability of the thermoelectric structure.

## THERMOELECTRIC STRUCTURE

There are two types of structures, those that integrate thermoelectric material into heat exchangers and use the heat exchangers to conduct the electricity to the thermoelectric material. This structure is only used for systems where the cooling powers exceed about 10 kW. The other type of structure, which covers the whole range from milliwatt to the above value uses thermoelectric modules with an electrically insulating interface between the thermoelectric couples and the heat exchangers. The heat exchanger can be just a cold plate. Both types of structures are examined as they can present reliability problems.

Figure 3 shows a photograph with from left to right: a thermoelectric element for integration into electrically conducting heat exchangers and thermoelectric modules: a large one, a small one for spot cooling and a 4 stage cascade module

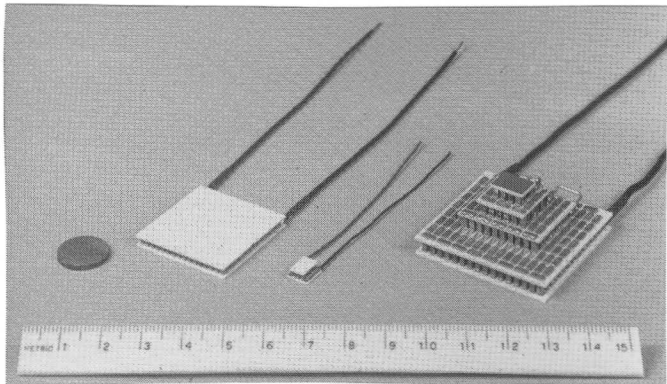


Figure 3 A thermoelement, 2 modules and a 4 stage module. Courtesy of Melcor Inc.

## Structure with electrically conducting heat exchangers

This structure contains the following components:

- thermoelectric material ( abbreviated to TE material )

- interfacing of the TE material ( chemical and mechanical aspects )
- heat exchangers ( electrical insulation from mass )

Thermoelectric material. There are two materials an N and a P type which constitutes the necessary thermoelectric couple. The only materials used since the late 1950's are doped alloys of bismuth, tellurium, antimony and selenium.

Thermoelectric material is made by two processes: The large majority of TE material currently manufactured is grown polycrystalline material ( rarely monocrystals ). A second technique is sintering. The reputable manufacturers have been commercialising stable material for several decades.

Interfacing. Companies not specialised in thermoelectrics but developing their equipments generally encounter difficulties which would have been avoided if expert advice had been sought at an early stage of development

Chemical aspect. Thermoelectric material is easily poisoned. The most notorious dopant is copper. Low temperature solder can poison the TE material so it must be protected by a diffusion barrier; the most common one used, is nickel as it can be plated onto the TE material. The nickel must be thick enough and not be deteriorated by the soldering.

Companies that decide to solder the TE material to copper must also put a diffusion barrier such as nickel on the copper. The solder is generally a 58 % Bi and 42 % Sn. When the above precautions are taken, the reliability of this interface is excellent. There is a good quality control test which consists in putting the TE material, soldered to its interfacing parts, into an oven for several weeks at a temperature recommended by the material manufacturer. The electrical resistivity of the TE material must be measured beforehand and afterwards, if it is unchanged then the interfacing can be considered stable.

Melcor, as an example indicates a maximum exposure temperature of 80° C. This accelerated aging test should be done at 90 °C with no measurable difference of electrical resistance after one week.

Another source of degradation is electro-corrosion generally due to the condensation of water contained in the gas ( air ). Obviously a water leak into the thermoelectric enclosure is a disaster.

Mechanical aspect. Cristal grown TE material withstands compressions of 50 MPa<sup>2</sup>. All structures of this type must be under high compression, the shear stress must be less than 15 MPa, and there must be absolutely no bending.

The sintered TE material is stronger mechanically than the grown TE material but the mechanical limitations of the interfacing are the same.

There are unfortunately numerous examples of failures of this type of structure because the people who designed the system did not follow the above guidelines. Generally the structures failed quickly after start-up. Companies who experience these situations are very reluctant to reveal the problems they encountered. Unfortunately the withholding of this information leads to others repeating the same mistakes.

The only two companies, known to the author, who have

successfully manufactured and installed systems with this type of structure, are Westinghouse and Air Industrie.

**Heat exchangers.** Electricity conducting heat exchangers mainly have one reliability problem which is: electrical insulation. For air heat exchangers the electrical insulation between adjacent heat exchangers can be obtained by an air gap if the gas is non condensing. However it is better to have an elastic seal made out of an organic insulating material which also serves as a seal to protect the enclosure with the TE material. This elastic seal also absorbs lateral thermal expansion that otherwise could create shear stress. Figure 4 shows a sketch of an air-air building block.

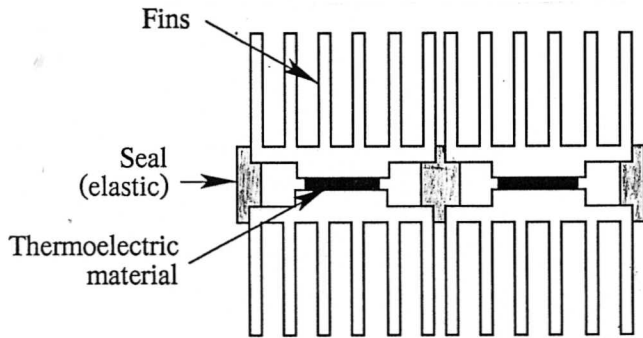


Figure 4 Sketch of an air-air building block

For the liquid side, there are presently two technologies: 1) where the liquid, such as water, is in direct electrical and thermal contact with the water. The thermal expansion of the liquid piping is absorbed either by elastic means, such as bellows, or by axial displacement of segments of the circuit, sealed by "O" rings. This technology generates electrolysis so the voltage on such a system must be small, opinions differ on having water in contact with electricity. The author's opinion is that it cannot have a high reliability because of the electrolysis and the risk of leaks.

2) where the liquid circuit consists of a continuous tube; this tube is dielectrically insulated from the electrical circuit of the TE material. Reliable dielectric insulations of 2500V DC have been confirmed by testing.

Other sources of unreliability are deposits on the heat exchanger surfaces that are in contact with the fluid. Such deposits increase the thermal resistance between the TE material and the fluid, thus, decreasing the cooling power. As the thermal resistance increases the temperature of the TE material increases. It can reach the melting temperature of the solder, this leads to serious degradation and failure.

#### Structures with thermoelectric modules

These structures represent a major portion of the market because they cover the cooling power span from the mW upwards. The modules can be cascaded, they use the same technology.

The basic component of these structures is a thermoelectric module purchased from a reputable manufacturer. Figure 3 shows a photograph of 3 modules and Figure 5 a module between a cold plate and an air heat exchanger.

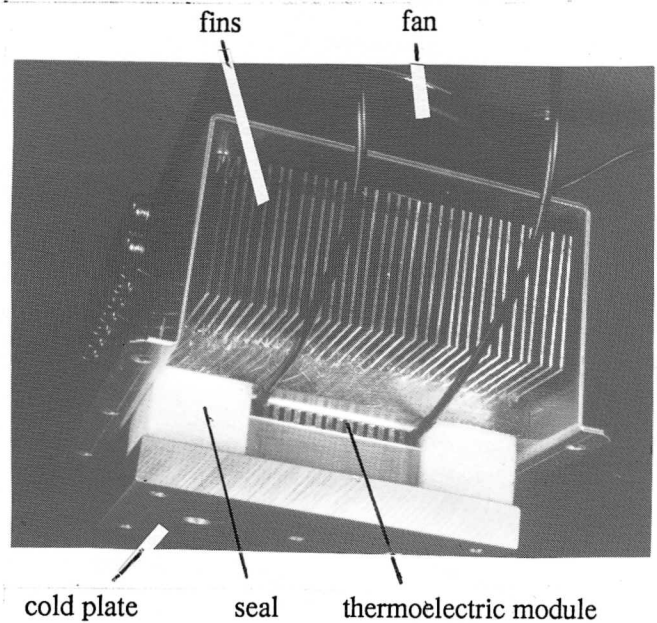


Figure 5 Thermoelectric cooling unit with a cold plate and an air heat exchanger to reject the heat. The seal has been taken off in front so that the TE module can be seen.

With this technology the responsibility of the thermoelectric part ( the TE module ) is basically that of the manufacturer of the module.

We will only address the case of installing modules with a ceramic interface as they represent essentially the total market. The installation of the modules must comply with the manufacturer's installation instructions.

The source of installation problems affecting reliability are related to :

- interfacing of the ceramic with the heat exchangers which can create mechanical stress on the module
- sealing of the thermoelectric enclosure

**Interfacing of the ceramic.** This topic has three related aspects : mechanical, thermal and electrical insulation

**Mechanical aspect.** The rule is that only one of the interfaces can be rigid which allows lateral thermal expansion between the hot and the cold ceramics. If there is only one module in a TE rigid structure then sometimes both sides are rigidly bonded.

This is the case with small single modules and cascaded modules where a small component is bonded to the cold ceramic. This component must either have no mechanical linkage with the rest of the structure or have very flexible links so that stress is not transmitted through the mechanical link. The matching of thermal coefficients of expansion becomes important as the temperature differences increase.

The interfacing techniques can be more or less rigid

**Rigid interfacing:** Solder and glue (thermally conducting epoxy) constitute a rigid interface

**Non rigid interfacing:** There is a whole range of techniques, typically:

A dry pressure contact is sometimes used. It has a high thermal resistance and a high friction factor.

Thermally conducting grease is good because it has a low friction factor.

Thermal pads are used extensively in electronics because they conduct the heat and absorb thermal expansion. They can also incorporate a dielectric insulation.

Modules are assembled into systems preferably under compression between two thermally conducting plates. These plates must be sufficiently flat and rigid so as not to bend during or after the tightening process. The recommended flatness is 0.02 mm per 2 cm which represents an asperity ratio of 1/1000.

Incorrect mechanical assembly of the thermoelectric structure is the major source of failure. The failures are generally of the early failure type. Generally the ceramic cracks and this can be detected by a voltage breakdown test.

Thermal aspect. The interface resistance depends on the type of interface. A soldered interface has a low thermal resistance, it is low enough to be negligible compared to the other thermal resistances of the thermal circuit, e.g: less than  $0.01 \text{ K} \cdot \text{cm}^2/\text{W}$

This technique is generally used on the hot side where the heat flux ( $\text{W}/(\text{m}^2 \cdot \text{K})$ ) is the greatest.

Epoxy interfacing has a much higher thermal resistance but it is much easier to use because there is no danger of overheating as with solder.

A thermal grease (silicone with zinc oxide) has a thermal resistance of the order of  $0.3 \text{ K} \cdot \text{cm}^2/\text{W}$  which can increase with time especially if insufficient pressure is maintained at the interface. This is a gradual failure and one of the major reasons for a drop in performance.

Electrical insulation. A great many applications only require one module, where the operating voltage is 12 V maximum, so insulation generally is not a problem because the ceramic is an excellent insulator for this level of voltage.

When voltages are much higher, such as 100 V, the ceramic when new is still an excellent dielectric insulator. The high purity alumina when used with a zinc oxide thermal grease interface under a pressure of 10 MPa holds up to a dielectric DC voltage test in excess of 1500 V. After several thousand on / off cycles and vibration tests, dielectric insulation is maintained.

Problems arise when the structure bends the ceramic and creates microcracks in the ceramic. As a result the traces of flux used to solder the copper straps to the thermoelectric material migrate into the cracks and creates shorts.

Sealing of the thermoelectric enclosure. Sealing is very important as moisture must not penetrate into the TE material enclosure. If it does there is electro-corrosion that degrades the thermoelectric material and the copper bus bars between the pieces of thermoelectric material become oxidized.

The seal around this enclosure must be reliable over the equipments life cycle. A major source of moisture leakage is where the electrical leads enter and exit the enclosure. The wires should either go through a sealed feed-through or must be stripped of their electrical insulation and go through, for example, an epoxy seal. A leakage causes a gradual failure which leads eventually to a total failure.

The proven procedures to detect early failures and long term failures of these structures are:

- Cycle the TE structure by turning on and off the electrical current so as to obtain temperature differences in excess of those of the most severe operating conditions.
- If there are specific vibration requirements then they

should be followed.

- If there are no specifications of the equipment relating to vibration or shock, the TE structure should be installed on a vibrating table and vibrated at the frequency of the power line (50 or 60 Hz) with accelerations on the structure of 10 g peak to peak.

When these two tests have been satisfied then the early failures are eliminated. If these test are prolonged then random failure of the TE structure is detected.

## AUXILIARY EQUIPMENTS

The study presented on laboratory equipments showed that 97 % of the failures came from the auxiliary entities. This fact has been amply confirmed over the years through experience.

The auxiliaries consist of a power supply and controls, depending on the application there can be fans and or

### Power supplies

Thermoelectrics require a DC current with an AC voltage ripple of preferably less than 10 %. All that is needed when reliable DC power is available at the necessary voltage is on and off switching.

Most frequently the AC power source is 110 V or 220 V, there are two types of converters

- 1) transformer and a rectifier.
- 2) rectifier, high frequency chopper (above 10 000 Hz), transformer and rectifier.

The rectifiers can be controlled or not which means variable output voltage or constant output voltage.

Among the converters weaknesses are the capacitors used in the rectifier. The back emf of a thermoelectric system is a well known source of problems. When the system is switched on and off, or the polarity inversed, during the time when there is still a temperature gradient across the thermoelectric material the thermoelectric structure sends back into the power supply an electrical current that can damage it. This is generally an early failure which should be detected during development of the system.

The reliability of these power supplies varies tremendously with their quality and complexity. The study cited in the beginning found a failure rate of 10 %, however in general power supply failures represent between 30 and 50 % of total system failures.

### Controls

Equipment controls can be simple on-off switches on DC from a battery with no safety devices, or complex microprocessor controlled systems.

There are two aspects to the controls

Generally a temperature or a parameter related to a temperature or a heat flux needs to be controlled.

Depending on the required stability of the temperature, the output signal can be either: yes/no or proportional.

- Yes/ no, controls an on/off switch on the electrical circuit.

- An intermediate solution is to do parallel-series switching on the electrical current.

- Proportional output power, requires a signal either analog or digital, that the power supply interprets as a directive to give out a variable voltage or current.

Besides the control aspect there is the safety aspect. Thermoelectric systems should have safety controls. Early detection of abnormalities can increase the availability of the system. there are two types of safety controls, those that indicate abnormal conditions which do not require immediate shutdown and those which do require immediate shutdown.

- The most important safety control is on the maximum temperature at the hot side of the TE material or module.

When the maximum temperature is above the upper temperature limit of the normal operating range, the system must be shut down.

- When the electrical current through the thermoelectric circuit exceeds an established value then something is wrong and the system must be shut down.

- Fluid flow on the heated side is critical because no flow leads to excess hot side temperatures. To check the fluid flows the voltage and amperage of the pumps and fans can be monitored and there should be a direct measurement of the flow for example by measuring a pressure drop across the thermoelectric structure.

#### Fans, pumps and air filters etc...

This is rotating equipment that can lead to a wearout failure. Quality as always is the main reliability parameter, nevertheless dirt can damage a fan and solids in the liquid can damage pumps, corrosion can also take place. Air filters require maintenance, lack of maintenance can lead to clogging of the filter which causes decrease of the air flow until it is below the minimum level set for the safety control to shut down the system.

This category of entities require a great deal of care especially when dealing with production of very few units.

#### STRUCTURAL AND OVERALL RELIABILITY

The failure rate  $\Lambda$  is the probability of a failure to happen in a given interval of time divided by the interval of time, as the interval of time decreases to zero and assuming that the entity has had no failure<sup>3</sup>

The Mean Time Between Failure MTBF can be expressed in most cases and when the repair time is short, as:

$MTBF = 1/\Lambda$   
Concerning the reliability of thermoelectric structures it is useful to introduce the number of components that can be either the number of thermoelectric elements, or the number of thermoelectric modules in the structure. When comparing systems these numbers should be introduced.

The study on the laboratory equipment covered ten years. Assuming that all the failures were reported (106) and that the equipments were all in operation 30% of each working day, this corresponds to a total of  $90 \cdot 10^6$  hours of operation.

The above cited study did not give any details on the thermoelectric modules or the number of thermoelectric modules in each type of equipment, but knowing the cooling powers involved it is estimated that there were an average of 4 modules per equipment. As there were 3 failures of thermoelectric structures we find for the thermoelectric structure

Te structure  $\Lambda = 3/(4 \cdot 90 \cdot 10^6)$

Te structure  $MTBF = 120 \cdot 10^6$  TE module\*hours.

System  $MTBF = 4 \cdot 10^6$  TE module\*hours

A prototype thermoelectric air conditioning unit has been in operation for 10 years on the french railways accumulating over 40 000 hours of operation. without a thermoelectric failure. The system contained about 7000 thermoelectric elements so the failure rate  $\Lambda$  is assuming a confidence level of 50 %<sup>3</sup>

TE structure  $\Lambda = 0.7/(40\ 000 \cdot 7000) = 2.5 \cdot 10^{-9}$

TE structure  $MTBF = 400 \cdot 10^6$  element hours

The author does not have any valid overall system MBTF values because no large systems has ever been manufactured in sufficient quantities to have the auxiliaries properly tested.

All this means that thermoelectric structures are extremely reliable.

The auxiliaries increase the failure rate by a factor of about 30, one can expect them to be independant of the number of modules except that the more there are modules more likely is the system to be complex.

#### CONCLUSIONS

Thermoelectric systems because there are very few moving mechanical parts essentially fans and pumps, have inherently a very high reliability. We have shown that the thermoelectric structure is the most reliable entity on the condition that it has been correctly developed and tested. Small systems with a few thermoelectric modules have for the thermoelectric structure a  $MTBF$ 's of the order of  $120 \cdot 10^6$  thermoelectric module\*hours.

The overall system MBTF is about 30 times smaller.

Large systems with with thermoelements intergrated into the heat exchangers have a thermoelectric structure  $MTBF = 400 \cdot 10^6$  element hours

All this shows that thermoelectric cooling systems when properly designed and tested have extremely high reliabilities

#### Acknowledgements:

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