# Dummy Loads and Smart Choices

### Bird Technologies Group Applications Engineer

There has been a considerable amount of attention lately regarding the transformation of analog communications systems to digital. With the FCC's recent authorization to permit certain FM stations to implement separate antennas for analog and digital signals and with DTV in place, the question often comes up, "What load is appropriate for my application?" This application note attempts to address the design differences, maintenance and environmental considerations that are important when choosing a termination.

The purpose of a load or termination (also known as a "dummy load") is to absorb RF energy and turn it into heat. Many times the load takes the place of an antenna during transmitter testing. Other applications where terminations can be found are:

- Reject Loads
- Hybrid Combiners
- Isolators / Circulators
- Transmitter Tuning
- System Testing & Calibration

An *ideal* load will provide a precisely matched absorption of unlimited RF energy over an unlimited frequency range while maintaining a perfect match (a VSWR of 1.0:1).

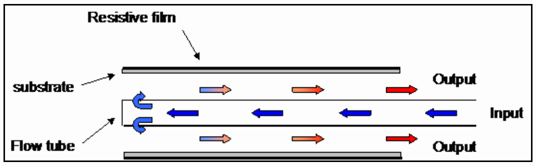
In the real world, the matching quality of the load varies with frequency. Typically the VSWR of a termination rises with increasing frequency, with the usable frequency range depending on the point at which the VSWR becomes intolerable. Power handling capabilities depend on physical size, construction, duty cycle of the applied signal and more. Selection of the optimum load for a given application involves a thorough understanding of load characteristics and design factors.

## Design Considerations

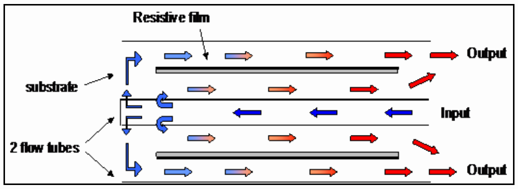
### Types of Loads

Following the laws of physics, a termination or load converts RF energy into heat. In most terminations, a resistive element is the device used to convert the RF energy into heat. For some applications, water is the means of conversion. Ideally, the heat should be disposed of in the quickest manner possible. To dissipate heat, the resistor is immersed in one of several dielectric mediums: air, water, oil or the combination of water and ethylene glycol. The heat transfer characteristics of the dielectric material determine the properties of the load and its suitability for various applications.

**Water-cooled loads** use pressurized water of proper temperature and flow rate to carry heat away from the resistive element. The water-cooling system can be sub-divided into two groups: water that is contained totally inside the resistor and water that flows on both the inside and outside of the resistor. See figures 1 and 2 below. The high-strength compound of the resistor tube is a good thermally conductive material, so that the heat generated by the RF energy is readily conducted through its comparatively thin wall. This substrate compound also essentially isolates the water electrically from the fields inherent to the coaxial line.



**Inner Water Flow Resistor**
**Figure 1**



**Inner and Outer Water Flow Resistor**
**Figure 2**

The generated heat is carried away by the water passing over the inner or inner/outer resistor surface. Unlike other terminations, there is practically no heat transfer to the outer housing of the load, even under full power application. Therefore, a very accurate measurement of power absorbed by the load can be easily calculated by the following formula:

$P = 0.263 (T_1 - T_2)$ GPM

Where: P = RF power in kilowatts
$T_1$ = Outlet water temperature in $^{o}$C
$T_2$ = Inlet water temperature in $^{o}$C
GPM = Water flow in gal/minute
0.263 = specific heat of water, turbulence, and thermal conductivity factor

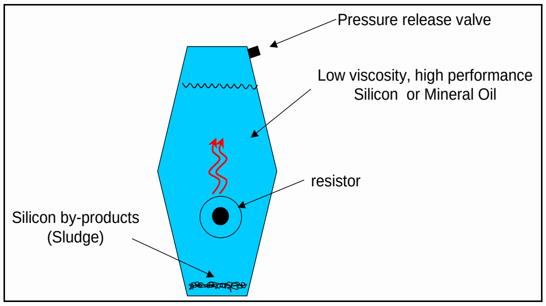
Loads with water as the coolant are by far the most efficient in transferring heat. Because they are the most efficient, they are also the smallest in size and have high power handling capabilities (up to 80 kW) and they can operate in any installation orientation.

For those installations that do not have water access or good water quality but still desire high power capabilities, Bird manufactures a water-cooled load (Moduload series) that is completely self-contained.

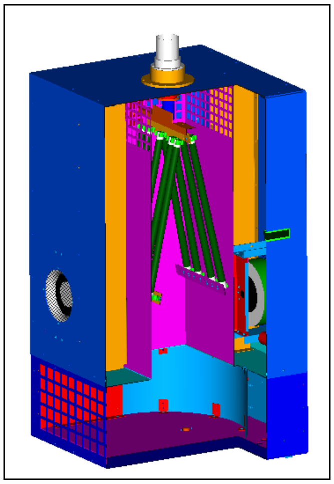
The closed-loop cooling system of the Moduload series consists of three basic sections: the RF load assembly, the control system and the heat exchanger system. The RF load assembly dissipates the RF energy and pressurized water acts as the main coolant however, the Moduload series provides its own heat exchanger to quickly reduce the temperature of the water before it is pumped over the resistive element.

**Oil-dielectric loads** surround the resistive element with oil, which transfers heat to an exterior, finned shell for dissipation into the surrounding air. See Figure 3. Oil-dielectric loads consist of a carbon film resistor on a ceramic substrate. The resistor is enclosed in a exponentially tapered housing. This provides a linear reduction in surge impedance directly proportional to the distance along the resistor. When surrounded by the dielectric coolant, the characteristic impedance is therefore: 50 ohms at the front (connector end), 25 ohms at the mid-point and zero ohms at the rear where the resistor joins the housing, forming the return conductor of the coaxial circuit. This produces a uniform, practically reflectionless line termination.

These loads may be divided into two sub-groups: devices using only exterior cooling fins to radiate heat and devices using cooling fins combined with electric blowers. With the installation of electric blowers, air is forced past the cooling fins for an increase in power handling capability.



**Classic rhombic shaped oil-dielectric load**
**Figure 3**



**Air-cooled Load**
**Figure 5**

**Air-cooled loads** use the properties of moving air to transfer the heat away from the resistive element. Typically these loads are equipped with fans to move the air past the resistors. This type of load uses multiple tubular ceramic resistors combined in parallel. This type of load design will also produce a very uniform and almost a reflectionless line termination. Electrically, this type of design, unlike other loads, appears as a high pass device. At dc, the load will be a short circuit and therefore can not be checked with an ohm meter.

Since this load does not use oil or water as the dielectric medium, they tend to be larger in size however, they are very low maintenance devices and quite reliable.

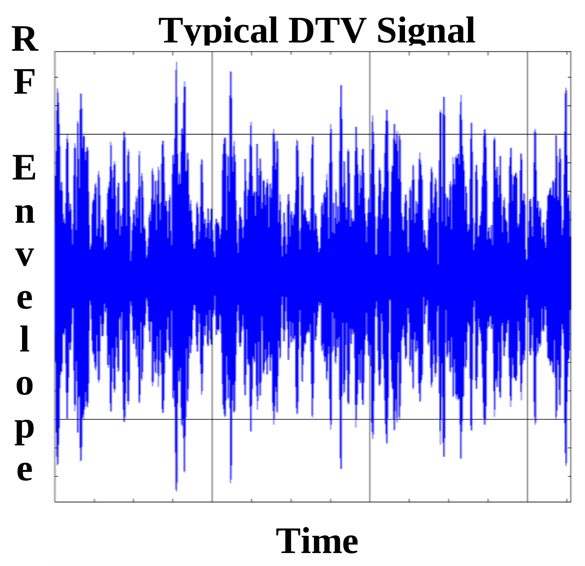
## Operation Considerations

**Power Handling Capabilities** Traditional communication systems in use today superimpose information on RF carriers. Typical modulation schemes include AM or FM for radio broadcasting and NTSC or PAL for television broadcasting. The TPO (total power out) of these systems show very little difference between peak power and average power. Globally, the traditional systems are being challenged by the digital revolution. The following table represents an outline of some of the systems that have either already been converted, or are in the midst of conversion to some form of digital modulation.

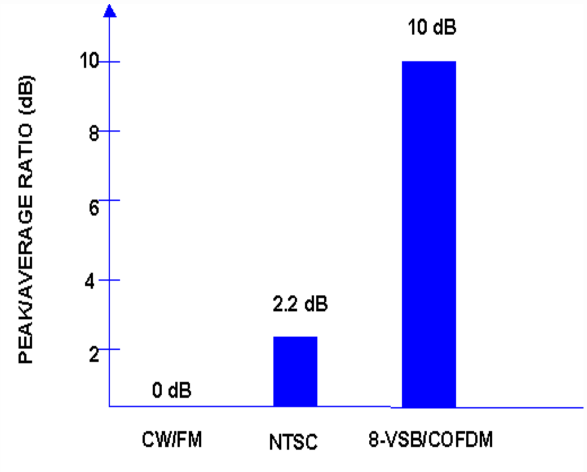
| System | Location | Modulation Type |
|---|---|---|
| Radio Broadcasting (iBOC) | U.S. | COFDM |
| Television Broadcasting | Europe | COFDM |
| Television Broadcasting (DTV) | U.S. | 8-VSB |
| Cellular Telephone | U.S. | TDMA, CDMA, GSM |
| Cellular Telephone | Europe/Asia | GSM |
| Paging | Worldwide | AM, FDMA |
| Two-way Radio | Europe/U.S. | FDMA, GSM |

In each of the above systems, intelligence in the form of voice or data is imposed on the RF carrier. Below is an example of a typical 8-VSB DTV waveform as viewed in the time domain. Unlike traditional analog signals, the digital signal contains peaks that appear above the main envelope of the waveform. In this particular example, the peak to average power relationship is about 6 dB and theoretically may be as high as 10 dB.

In addition to digital TV and radio, many stations multiplex or combine multiple carriers for transmission to a master antenna.

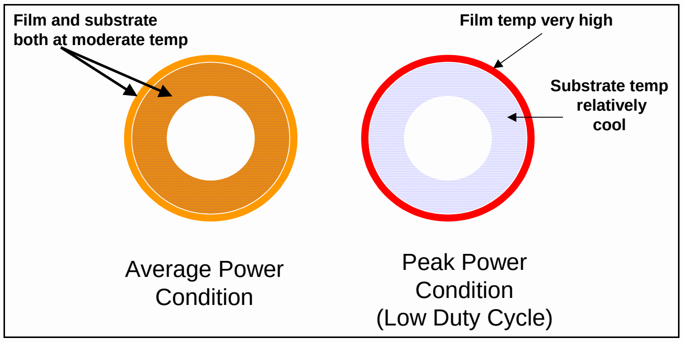


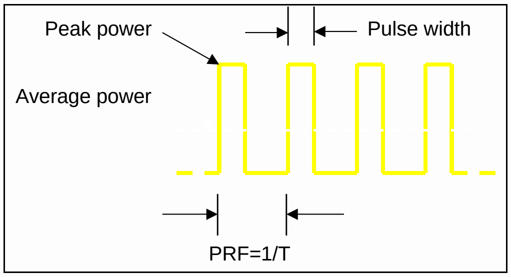
The result is a non-constant power envelope, i.e. large peak to average power ratios. When selecting a load, it is important to understand that certain load designs are better able to handle the high peak to average power ratios found in digital or multi-carrier signals. But first, let's examine what happens to a resistive element when a CW (continuous wave) signal is applied.



Looking at a cross section of a typical resistive element when a CW signal is applied, both the resistive film and substrate are heated evenly. However, when a digital or pulsed signal is applied to the same resistor, the peaks of the signal can instantaneously heat the carbon film. The carbon film will expand while the substrate will not which creates a mechanical stress. The film could physically be blown off the substrate.

**Cross section of resistors**





A general rule of thumb for pulse and digital applications is the duty cycle is such that the average power of the load is never exceeded. The following calculations work for rectangular pulses however, more complex modulation schemes must rely on statistical methods for peak values.

Let's look at an example of how one could determine whether a load can handle the peak or pulse power:

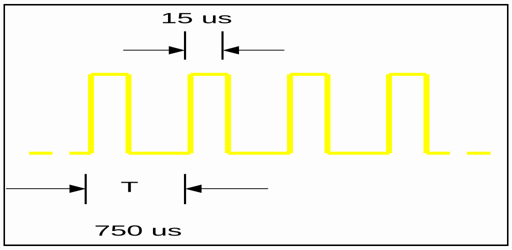
Pulse width ($\tau$) = 15 $\mu$s
Pulse Repetition Interval (T) = 750 $\mu$s
Pulse Repetition Frequency = 1 / T
Peak Power = 100 kW

**Duty Cycle = $\tau$ / T**

Duty Cycle = (15 x $10^{-6}$) / (750 x $10^{-6}$) = 0.02

***Average power = duty cycle x peak power***

*Average power = 0.02 x 100 kW = 2 kW*



In this example, a termination should be selected that has an average power specification of at least 2 kW or greater. In addition, it should also be verified that the specific load can handle the peak power.

Due to the mechanical stress between the film and substrate when instantaneous power is applied, a pulse width that is less than 1 $\mu$s is considered equivalent to 1 $\mu$s when calculating average power. Likewise, a pulse width that is greater than 5 ms is equivalent to CW when calculating average power.

### *Harmonic Contribution & RF Leakage*

*Whether the load is used for transmitter tuning or as the termination on a circulator, one should be aware of the harmonic and RF leakage contribution to the total power the load may be seeing.*

From the diagram below, not only will the load dissipate the power from the fundamental frequency, but it will dissipate the power found in the harmonics as well. If the harmonic content is not known, a load could be operating well above the specified power level which could reduce the life of the load or worse, result in catastrophic failure.

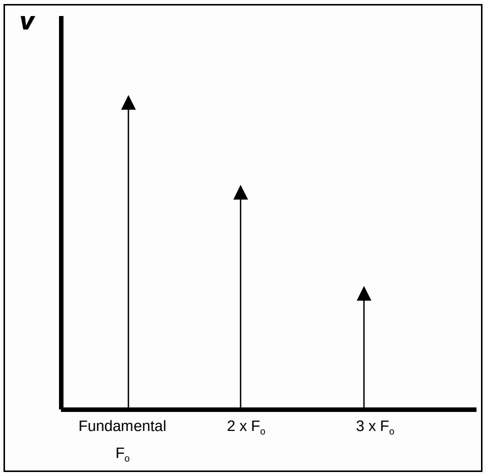
*Likewise, when using a termination with a circulator, combiner or isolator, port to port RF leakage may be contributing to the total power the load must dissipate.*

*For example, a circulator in a TV broadcast system may be adding additional power to the load as shown below.*

***Example:***

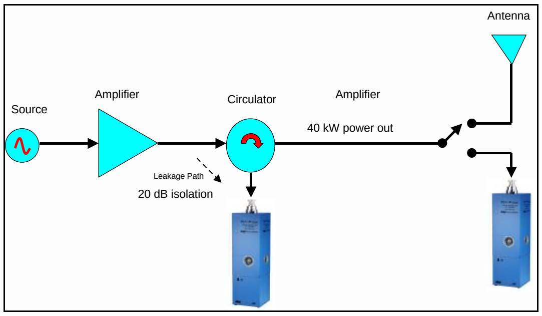
Typical forward power = 40 kW = 46 dBw
Isolation between circulator ports = -20 dB

The amount of power that would leak across the circulator to the load is:



**Harmonic contribution to total power**

That is an additional 400 W of power that is unaccounted for in the load requirement.



**RF Leakage Example**
**Figure 13**

### Altitude Considerations

When operating a load cooled by flowing air, the ability of the air to capture and transfer the heat away from the load is diminished. For this reason, the operating power level must be de-rated. Generally, the oil and Moduload series start to de-rate at 5000 feet above sea level while the air-cooled loads start to de-rate at 10,000 feet.

### Maintenance Considerations

When considering a load for your application, operating conditions and maintenance should be explored. Systems operating at high altitudes, extreme temperatures or with poor water quality can be a significant factor when making a decision.

### Water-cooled Loads

While many factors will impact a water-cooled load’s ability to dissipate energy, one of the most critical is the quality of the water used. Water must be of sufficient quality and quantity to allow heat transfer from the resistive element to the outside. Any internal heat build-up could result in a catastrophic failure or a decrease in the life span of the load.

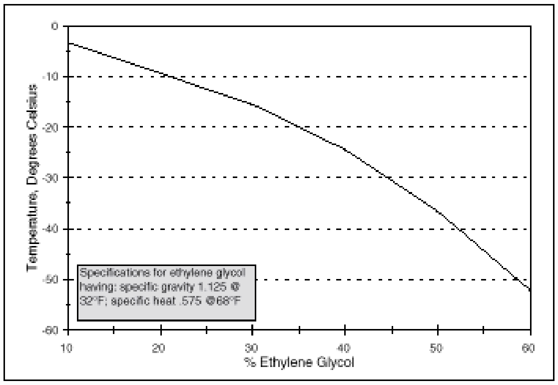
Water quality is measured in the United States as the amount of solids dissolved in the water and is expressed in “parts per million” (1 ppm = 1 mg per liter). Standards for drinking water (potable water) are established by the U.S. Public Health Service at a maximum of 500 ppm of total dissolved solids. The total ppm count could be many different types of materials, making it impossible to place a specific water conductivity figure on the limit. The hardness of water refers to the content of calcium, and magnesium salts, which may be bicarbonates, carbonates, sulfates, chlorides or nitrates. These salts in hard water form deposits or scale on the resistor as water is heated or evaporated. Think of scale as the particles that are left over from when a pan of boiling water completely evaporates.

Impurities and chemical additives in the water affect the electrical and thermal characteristics of the load. Salts in the water will result in a rapid increase in VSWR due to the accumulation of scale on the inside and/or outside surface of the ceramic tube resistor, depending on the water-flow design. Impurities and scale also increase the thermal resistance of the load, which can cause the load to overheat and fail. Because of the impurities and solids, salt-water (sea water) or any type of silty water should not be used for cooling the load.

**Resistive element with scale accumulation**

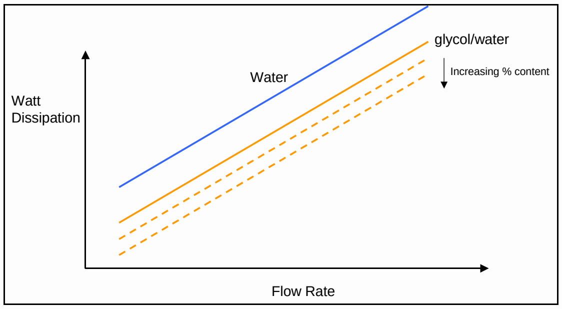
Equally, de-ionized water should not be used as the load coolant. De-ionization allows the removal of particles as small as ions from a solution and is used to purify water and remove salts and other impurities. However, since this water is ion-starved, it will chemically attack the brass, copper and aluminum found in the water system and re-deposit some of the metals on the resistor. As a result, the load will overheat and fail rapidly.

Distilled water is water which has been heated to the boiling point so that impurities are separated from the water, which becomes vapor or steam at 212 F (100 C). The steam is then cooled and condensed back into pure liquid form. The impurities remain as residue in the steam kettle. This distillation system removes organic and inorganic chemicals, heavy metals, volatile gasses, and other contaminants. Distilled water used as the coolant will yield the maximum life expectancy of the load and is the best solution if water quality is in question. Softened or de-mineralized water is also acceptable due to the lower amount of dissolved solids present.



**Temperature vs. % Ethylene Glycol**
**Figure 9**

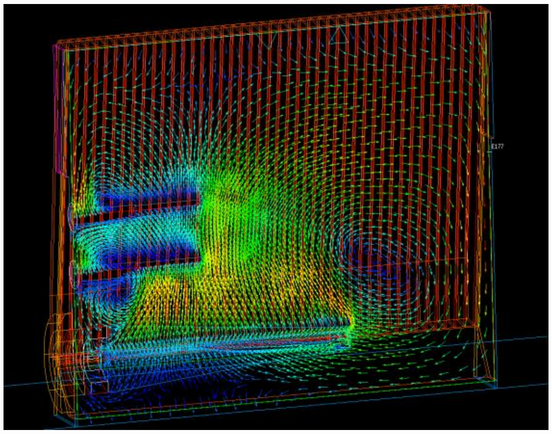
Where cooling systems are required to operate in below-freezing temperatures additives are needed to lower the freezing point. Using a mixture of water and ethylene glycol (antifreeze or Dow Chemical Company's Dowtherm SR-1) protects against freezing and has outstanding corrosion-inhibiting advantages. However, a 40% SR-1 to 60% water mixture is only half as efficient as water in taking heat away from the resistor. A 50/50 mix is less than half (43.9%) as efficient. Since these mixtures are less efficient coolants, de-rating of the power level of the load or an increase in the water flow rate is required. See Figures 9 - 10 above for general guidelines.



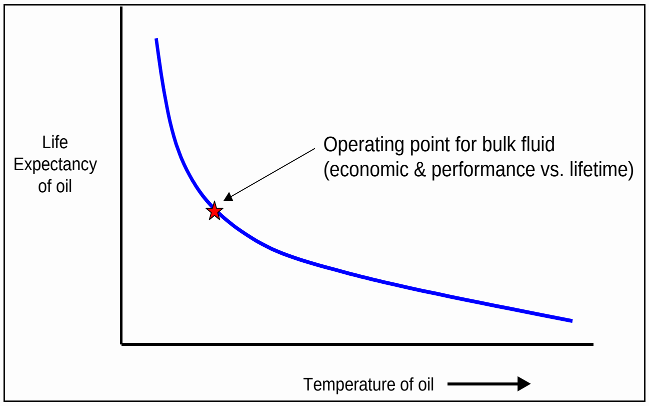
**Power Dissipated vs. Water Flow Rate**
**Figure 10**

### Oil-dielectric Loads

Oil-dielectric loads use silicone or refined mineral oil as the heat transfer medium, removing heat produced in the resistive element and transferring it to the finned outer shell and then into the surrounding air. Like the water-cooled loads, the life expectancy of an oil-dielectric load is directly related to the amount of internal heat produced. The maximum temperature rating for the oil and resistive film limits the power handling capability of the load. The oil must stay below its maximum temperature to ensure that the oil doesn't break down and form other compounds. Oil becomes more reactive to foreign substances at higher temperatures and can form compounds that do not have the same thermal or electrical properties of the original oil resulting in an increase in VSWR and potentially failure.



**Oil convection currents**
**Figure 11**



**Life Expectancy vs. Temperature**
**Figure 12**

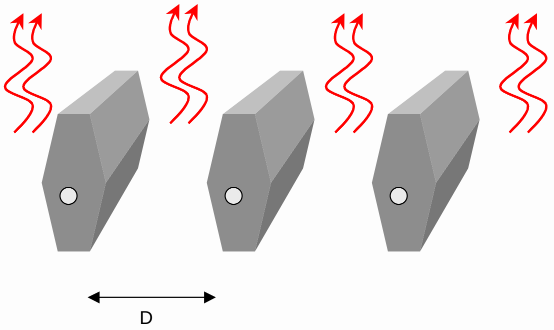
If a load is operated under worst-case conditions, 50 Hz, at maximum rated power and maximum ambient temperatures, the rate at which the oil breaks down is much greater and the oil should be changed every 100 - 250 hours of operating. If the same load were operated under less stressful conditions, 60 Hz, 80% of load rated power and 25□ C ambient temperature, the oil will need to be changed between 500 - 700 hours. Under the same conditions but at 60% of rated power, the life expectancy of the oil is greater than 4000 hours. See Figure 12. The condition of the oil can be determined by two indicators: color of the oil and any odor from the oil. Oil that is dark or has a burned or pungent odor should be replaced.

Adequate spacing between oil-dielectric loads is important to maintain since the cooling fins are radiating heat. Positioning the loads too close together or to a wall will raise the ambient temperature and as a result, increase the temperature of the oil.

Generally, space oil-dielectric loads as follows to maintain adequate convection between the loads:

1 kW load: d = 12” or 6” from wall
2.5 kW load: d = 24” or 12” from wall
10 kW load: d = 30” or 15” from wall

Likewise, placing a cover or shroud over the oil-dielectric loads or mounting the load too close to the ceiling will prevent proper air flow.



**Air-cooled Loads**

Since air is the heat-conducting medium of an air-cooled load, care must be taken to not impede the air flow and not exceed the maximum ambient air temperature. There is no need to filter the air as long as the air is reasonably clean.

Similar to the oil-dielectric loads, spacing between other loads should be kept at a minimum of 12” or 6” to the nearest wall.

In summary, when selecting a load, it is helpful to be able to answer the following question:

- What is the operating frequency?
- What level of power and type of modulation is being applied?
- What is the peak to average ratio of the signal being dissipated?
- Are there harmonics present on the signal that may add to the total power being seen by the load?
- Are there leakage paths from other components of the circuit that may be contributing to the total power level?
- What will be the typical ambient temperature of the surrounding air?
- Will there be adequate space between loads?
- What is the quality of water?

The chart on page 8 summarizes the qualities and characteristics of conventional loads.

| | **Water** | **Air** | **Oil** | **Moduload** |
|---|---|---|---|---|
| **Size** | small | large | medium | medium |
| **Weight** | light | moderate | heavy | heavy |
| **Initial Cost** | Low | higher | medium | medium |
| **Power** | high | moderate to high | low | moderate to high |
| **Maintenance** | complex | simple | moderate | moderate |
| **Peak Power** | moderate | highest | high | moderate |
| **Overload tolerance** | lowest | highest | moderate | lowest |
| **Altitude** | 5,000 ft | 10,000 ft | 5,000 ft | 5,000 ft |
| **External Temp.** | coolest | cool | hot | warm |