

# Large >60 gallon/day ‘pulse-tube’ oxygen liquefier for aircraft carriers

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**Abstract.** An oxygen liquefier using a large ‘pulse-tube’ or acoustic-Stirling cryocooler is described, which has a liquefaction rate in excess of 60 gallons per day (227 liters per day) as measured by the increase in weight of a storage dewar, from <20 kWe input. Several of these systems will be deployed on U.S. Navy aircraft carriers to provide shipboard liquid oxygen. Paths to improvement in future systems are identified, although it is noted that since the present system exceeds the required specifications, these improvements may not be implemented in the near term.

## 1. Introduction

Most liquefied gases are produced in large air-separation plants that operate continuously and have thermal efficiencies approaching 80% of Carnot. However, this technology does not always scale down well, and is ill-suited to producing cryogenics “on demand,” as it typically takes a small-scale ASU (air separation unit) over 8 hours to warm up [1]. An acoustic-Stirling or ‘pulse-tube’ liquefier, by contrast, can begin producing LOX in as little as 15 to 20 minutes. In addition, the operation is simple and virtually maintenance-free. For a mobile environment such as a warship, this is especially important.

Here, we describe an oxygen liquefier that will be deployed on Navy aircraft carriers, as part of the shipboard oxygen system. While in hindsight we could build a more efficient device today, this system meets its goals and it is hoped that successful deployment of multiple units will help this technology become more established. Given the opportunity to supply a system to the Navy on an accelerated schedule, we chose to use already-developed components in a novel configuration. Simplicity was favored over maximum performance, especially in regard to design of the vacuum vessel(s) surrounding the coldheads and their connection to the incoming gaseous oxygen. Simulations suggested that there would be ample capacity headroom, and indeed we were able to meet the program requirements in spite of the compromises.

## 2. Basic construction

The liquefier is based on our ‘2S362W’ acoustic driver, or PWG (pressure-wave generator) and our ‘2S241K’ coldfinger. The 2S362W driver produces approximately 15 kW of  $pV$  power from 20 kWe input; the 2S241K coldfinger is originally designed for use with our smaller ‘2S241W’ PWG, with a nominal input power of 5 kWe maximum. At the inception of this project several years ago, we had been developing the 2S241K coldhead for HTS applications, where it was believed that delivering cooling directly to the load (rather than through a pumped cryogen loop) was preferable. Hence, we



developed a large coaxial pulse-tube coldfinger, driven by the PWG through a long (>1m) transfer line to permit the coldtip to be mounted directly to the cooling load, while the PWG could be mounted elsewhere.

A solid model of the core system is shown in Figure 1 (the Navy and the other contractors prefer that we not show the integrated system as delivered). The three coldheads are connected to a common drive, capable of providing over 15kW of  $pV$  power (total) to the coldheads. Each coldhead has a collection dewar, and all three ‘buckets’ are connected to a drain which is then connected to a storage dewar. The coldheads are connected to the drive via flexible, corrugated hoses, which will inflict some acoustic losses. Driving multiple coldheads also risks positive feedback—if one coldhead gets colder faster, it will draw more power from the drive, accelerating its cooldown even more. Indeed, we have observed this during initial cooldown of these systems, but once all three coldheads are condensing oxygen, they are effectively isothermalized. Also note the gaseous oxygen delivery manifold, which has three separate 3/8” (1 cm) OD pipes, one to each coldhead, at the top of each collection dewar.

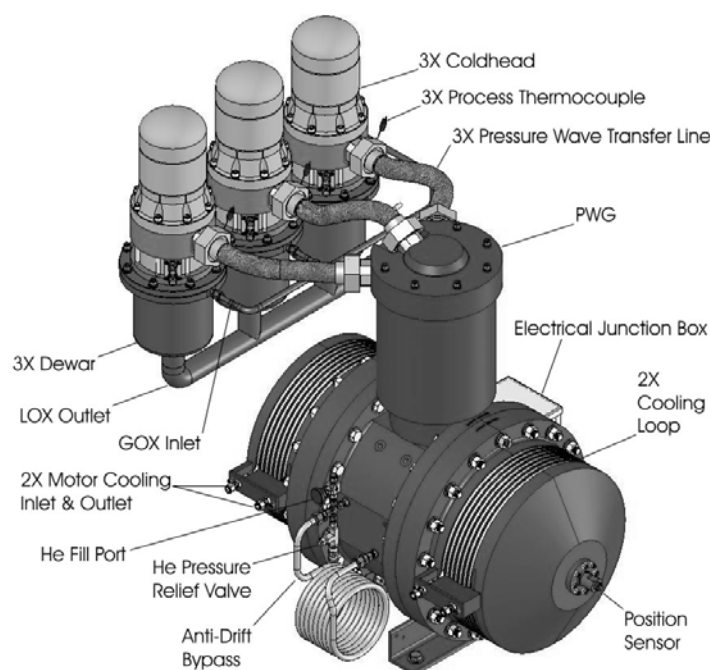


Figure 1: Solid model of core cryocooler assembly from the liquefier system, showing three coldheads on a common acoustic drive, and a ‘three-bucket’ collection dewar. For a sense of scale, note that the pressure-wave generator (or ‘compressor’) on the bottom is about 1 meter end-to-end.

### 2.1. 2S241K coldhead

The 2S241K coldhead, shown in section in Figure 2, was originally developed for direct cooling of HTS devices, specifically for fault-current limiters (as described in the original Department of Energy “Cryogenics Roadmap” [2], which attempted to assess the need for cryogenics to support the anticipated market for superconductors). Its coaxial design presents a salient cold zone, at the expense of some efficiency and with an increased risk of secondary flows. The coldhead can produce over 200W at 80K when on its companion “2S241W” drive, where it receives roughly 3.5 to 4 kW of  $pV$  power. On the larger 2S362W drive, each head receives approximately 5 kW  $pV$  power. To predict how the overall system will perform, before the coldheads are integrated, we make a series of measurements on the smaller system and extrapolate.

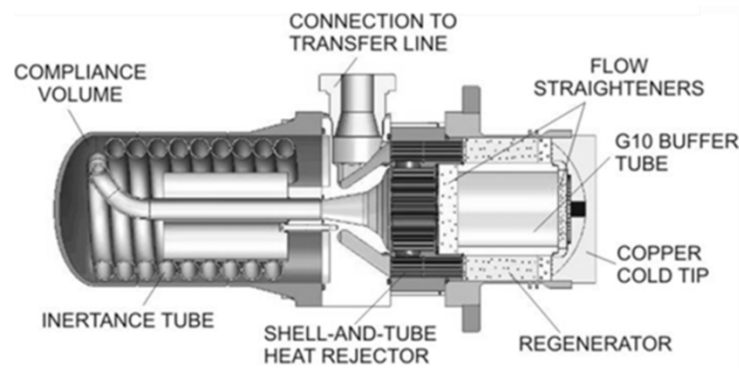


Figure 2: Cutaway view of the 2S241K coldfinger, showing the essential components.

### 3. Predicting performance of full system

Before assembling the full system, it is important to have confidence that the performance target will be met. Because the coldheads cannot be driven at the full-system amplitude when run individually on the smaller drive, we make a series of measurements on each coldhead at progressively higher input powers, in order to predict the performance of each coldhead when on the common drive. Figure 3 shows a 2S241K coldhead connected to a 2S241W drive for an individual coldhead test, and Figure 4 shows a load curve at 4.4 kWe input for one of the coldheads. The performance is measured up to 108K, as this is the saturation point of oxygen at 50 psig (or 0.446 MPa absolute), the storage dewar pressure limit.

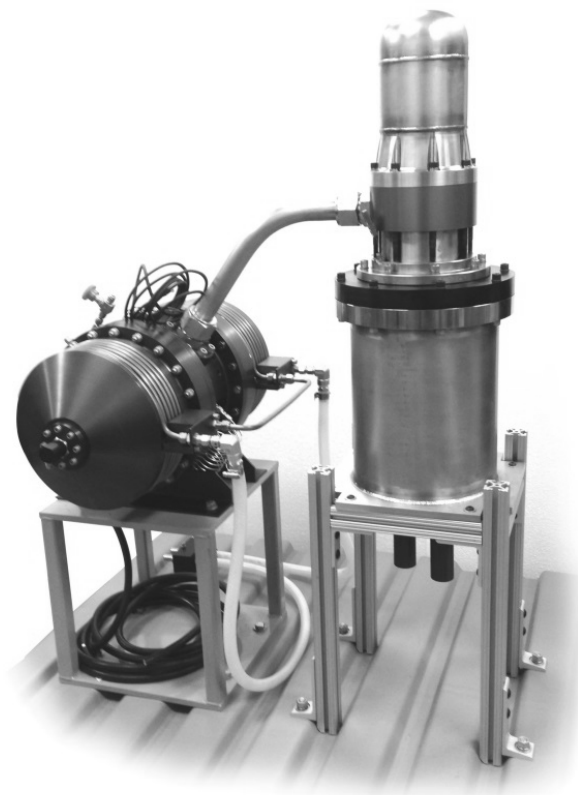


Figure 3: Single 2S241K coldhead driven by a 2S241W (~5kWe) PWG, for individual coldhead testing.

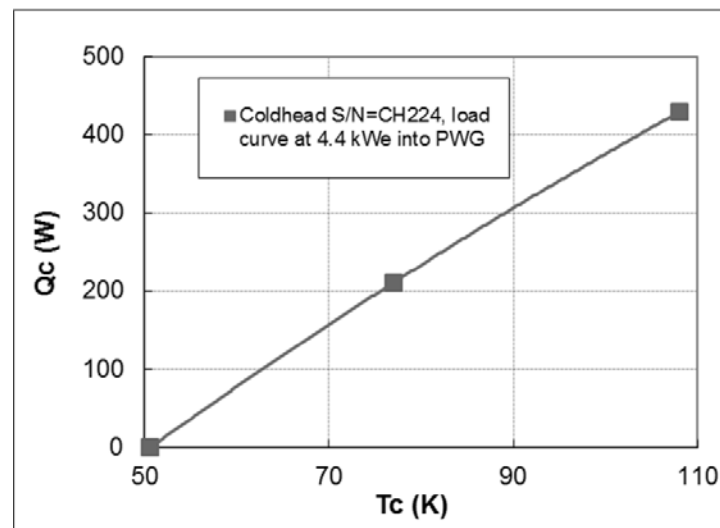


Figure 4: Load curve for a single 2S241K coldhead.

Next, each head is measured at a sequence of increasing input powers, so that the performance on the common drive can be estimated. The electric input power is not as good a guide as the acoustic drive level,  $p_1/P_m$ , where  $p_1$  is the peak acoustic pressure and  $P_m$  is the mean (charge pressure). These quantities are known from measurements on early prototypes; thus, despite any difference in efficiency between the smaller and larger drives, we can use the acoustic intensity,  $(p_1/P_m)^2$ , to extrapolate to the eventual drive level when integrated into the big liquefier. Figure 5 shows a power curve and an acoustic intensity curve for one of the coldheads. Note how the acoustic intensity curve is very linear, allowing for a confident extrapolation. The curvature in the cooling capacity versus power graph may be from higher losses in the transfer line, for instance, but the pressure wave is measured right at the coldhead, so the acoustic intensity extrapolation is not affected.

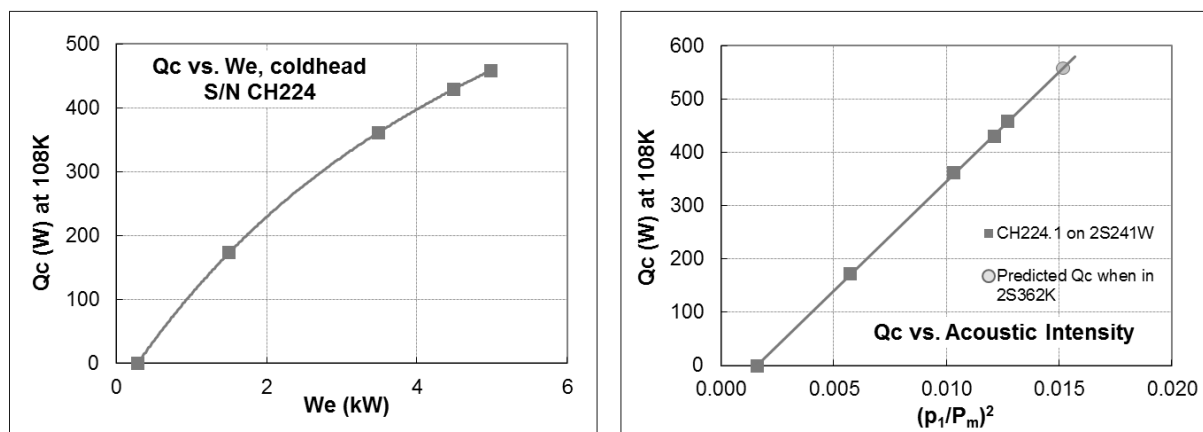


Figure 5: Cooling capacity of a 2S241K coldhead on a 2S241W drive, versus input power (left) and ‘acoustic intensity’ (right).

Not all coldheads have such linearity in acoustic intensity, however. Figure 6 shows another coldhead tested in the same manner, where the acoustic intensity curve is not so linear. This coldhead is also not quite as good as the first one at its nominal input power; we suspect that small flaws in the flow straighteners on either end of the buffer tube (for instance) may seed convection that grows worse at higher amplitudes.

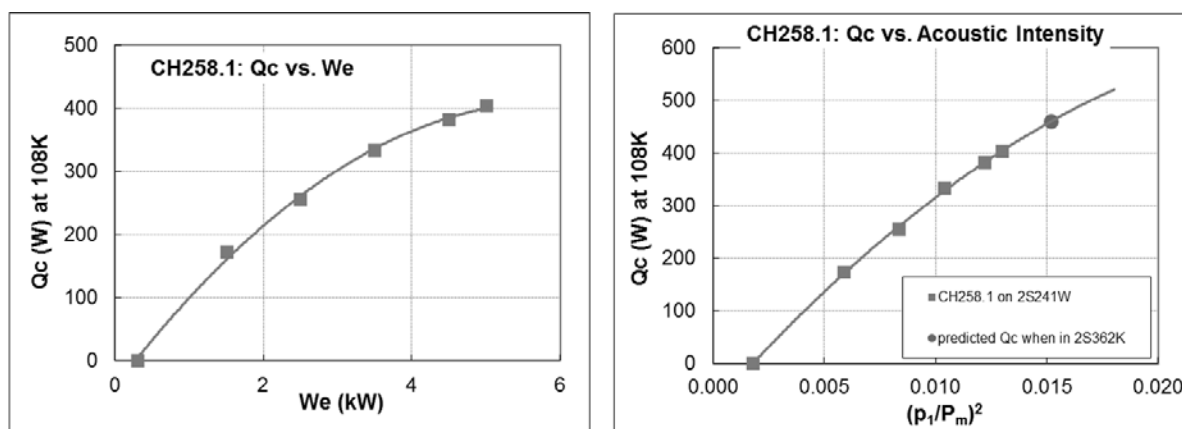


Figure 6: Cooling capacity versus input power (left) and acoustic intensity (right) for a second coldhead; note how the the acoustic-intensity curve is less linear, resulting in lower cooling capacity at high amplitudes.

### 3.1. Combined cooling power and performance prediction

For the three heads in the system discussed here, the combined prediction of cooling power at the higher acoustic intensity they will experience on the common drive is 1360W at 108K. At 0.446 MPa (50 psig), it takes about 4W per liter per day to bring oxygen from ambient to liquid, so this predicts an upper bound of 340 liters (90 gallons) a day production rate, not including any losses.

## 4. Experimental results and discussion

In actual tests, the ‘useful’ liquefaction rate was measured by observing the weight of the storage dewar on a calibrated scale. The results of one typical run are shown below in Figure 7:

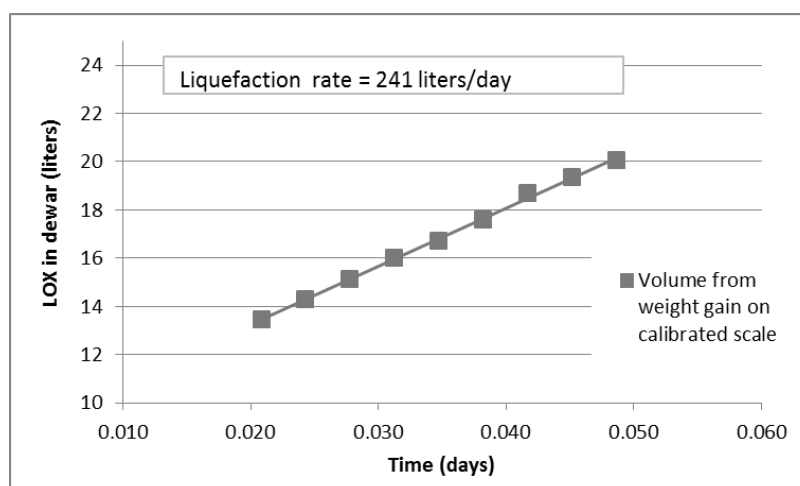


Figure 7: Actual liquefaction data from the completed system, from accumulated weight of oxygen in the storage dewar.

The liquefaction rate obtained from the slope of the curve is 241 liters per day, much less than the upper bound prediction of 340 liter/day. Dewar boiloff and transfer hose losses account for some of the difference, but our boiloff-rate measurements (and the manufacturer’s specifications) suggest these losses are only about 10 to 15 liters per day. The actual coldtips on the coldheads run a little colder than the condensation temperature (there are condensing fins attached to the coldtips to enhance the condensing surface area), lowering the fundamental capacity of the cryocooler a little bit. Still, this effect is estimated to be less than three or four liters per day in reduced capacity. Thus, based on what

we know, we would naively expect to be liquefying 320 to 325 liters per day, rather than 240. There are two areas of focus where we believe additional losses are occurring:

- **Acoustic transfer lines.** These connect the coldheads to the common drive, and have internal corrugations that are capable of causing significant acoustic dissipation due to turbulent flow. The acoustic drive level used to estimate the performance of the coldheads is actually measured on the driver side of these transfer lines, as there are no pressure taps available on the coldheads in the final configuration. It is likely that the acoustic power is being attenuated in these lines; we could estimate that attenuation by modifying a spare transfer line with a pressure tap on the coldhead side.
- **Collection dewar feed gas space.** As mentioned in the Introduction, the dewar design and process gas handling were designed for simplicity rather than maximum efficiency. The feed gas comes into the collection dewars in the annular space around the regenerator, where there is a steep thermal gradient (ambient to 108K in less than 8cm). Of course, this reduces the cooling capacity from what is measured in the separate coldhead tests, which are done with the coldheads in a vacuum and wrapped in MLI. The intent was for the gas to be precooled by contact with the regenerator wall, thus offsetting some of the reduced capacity of the heads by increasing the efficiency of the liquefaction process. However, it is possible that the gas in the annular space is vigorously mixed by the incoming flow, so it is not stratified.

For future builds, we could potentially troubleshoot some of these issues by adding a feedthrough to the collection dewar, so that the actual cooling power of each coldhead could be measured *in situ*.

## 5. Conclusions

Chart, Inc. has successfully built and tested an oxygen liquefier for the U.S. Navy that will be deployed on active carriers. While the specifications have all been met or exceeded, we have shown that there are specific paths to improvement, such as:

- Improved quality control of coldhead components (all coldheads should perform nearly the same)
- Improved collection dewar design (to reduce losses around the regenerator associated with the feed gas)
- Improved acoustic transfer lines—these could possibly be made solid, or be made with smooth liners, so that the acoustic losses are reduced.

These improvements could all be made without changing the outer configuration of the unit, and so could conceivably be applied to the Navy application, where considerable infrastructure has been built around the core liquefier.

In more general applications, it may be that the multiple-coldhead approach is not advantageous, nor cost-effective; and the coaxial design may confer no special advantage when it comes to liquefaction of pressurized process gas, such as well-head LNG production or zero-boiloff storage or cryogenics. A single inline head by its nature requires a more complex vacuum vessel; because the cold heat exchanger is embedded, the most practical construction for process applications at large scales (hundreds of watts of cooling and above) is to use a shell-and-tube heat exchanger in the cold zone as well as the warm zones. This requires that the vacuum vessel have insulated process lines through the outer vacuum-vessel wall that connect to the cold heat exchanger (as well as a penetration on the top for the exit of the warm heat exchanger and inertance tube). The greater complexity, however, results in fundamentally more efficient operation, as the cold zones of the coldhead are vacuum insulated and the process gas goes directly to the cold heat exchanger.

Ultimately, it may be the case that the increased cost and complexity of the inline head's vacuum and process components may be offset by other savings, in parts count if nothing else (i.e. if a single head can be as good or better than three in parallel). There is also no particular reason to mount an inline head remotely from the acoustic drive; rather, it would be coupled directly. This results in a

more efficient transmission of acoustic power to the coldhead and the elimination of another part in the assembly, as well as some alignment issues, if indeed one coldhead can be used.

In conclusion, while more efficient configurations are possible, the choice to build the current system out of available components in a simple construction resulted in timely delivery of a liquefier that meets or exceeds all program requirements. It is hoped that deployment of these systems will result in greater acceptance of acoustic cooling technology.

## References

- [1] See, for instance, <http://www.shin-tek.com/cryogenic-oxygen-plant.html>
- [2] M. J. Gouge, J. A. Demko, B. W. McConnell and J. M. Pfotenhauer, "Cryogenics Assessment Report," Oak Ridge National Laboratory (2002)  
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