Lessons learned
from the
NEPTUNE power system and other deep-sea adventures

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Abstract – **The development of underwater science systems presents some challenging technical issues. It seems that the best efforts of the engineers and scientists involved are sometimes inadequate, and projects that once seemed straightforward end up being late, or over-budget, or cancelled. This paper will review some of the lessons that may be learned from the examples of three science projects in the deep ocean: the DUMAND neutrino detector, the H2O observatory, and the power system part of the NEPTUNE regional cabled observatory.**

Introduction

A couple of years ago I was sitting on a plane at the airport in Seattle, waiting to go home. The pilot's voice came over the intercom, announcing a delay of about an hour. Evidently the light bulb in the wingtip position light had failed, and the sealant for the assembly would take almost an hour to cure.

I was evidently the only passenger on board who was not upset at the delay. I knew that the sealant had been through a long and careful process that qualified it for this use (keeping rain out at a relative speed of over 800 km/hr), and that the procedure for applying it and curing it had been similarly checked.

I also knew that the seats on the plane were more comfortable than the hard plastic ones in the terminal, and I was the only passenger to stay aboard when given the opportunity to go back to the terminal. That decision got me a cognac to ease the pain of waiting!

I tell this story because of its relevance to the business of constructing under the ocean a very large neutrino telescope. It is the hope of this paper to support the goal of this workshop to advance relevant technologies, by drawing lessons from some past efforts that have much in common with the present endeavor. Those lessons have to do with mission assurance: a formal process for ensuring that systems will perform reliably in service.

It is, unfortunately, a characteristic of the "lessons learned" genre that mistakes are emphasized. So it will be with this paper. However, we discuss mistakes in the hope of learning from them (ideally, how to avoid them), and assuredly not in order to assign blame. I sincerely hope I offend no-one.

The three projects I will review here may be already known to the participants at this workshop. They are the DUMAND project (to construct a neutrino telescope), the H2O Observatory (for ocean science), and the power part of the NEPTUNE project. (Another paper at this workshop covers broader aspects of NEPTUNE, including the science.)

These projects have much in common with one another. Each involves an effort to put scientific equipment in the deep ocean (around 5 km): each uses a telephone-type cable to bring power under the water and communications back to shore; each has encountered difficulties in implementation.

DUMAND

The aim of the DUMAND (Deep Underwater Muon and Neutrino Detector) project was to install an underwater observatory 4800 m below the surface at the bottom of the ocean near the Big Island of Hawaii. The array site was 30 km due west from the Kona Coast of the Big Island of Hawaii, see Figure 1, and connected to the shore station by a 12-fiber cable. The power system supplied up to 5 kW of electrical power at 350 Vdc, using a seawater return system.

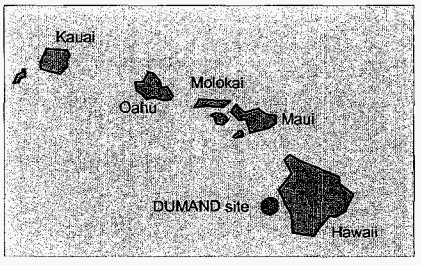

Figure 1 DUMAND site near Hawaii

The purpose of the observatory, an international collaboration centered at the University of Hawaii, was to detect the Čerenkov radiation from high-energy neutrinos. From the pattern and timing of the radiation, the direction of the incoming neutrinos could be ascertained. From this, for example, it was expected that high-energy astronomy would yield insight into active galactic nuclei, and more.

The first major installation was to be a test of 3 detectors in a vertical string. Things did not go well. A cable was laid from shore to a junction box, and a first string of detectors was installed from the junction box at the end of 1993. It stopped operating within a few hours, because of a leak. Figure 2 shows a Junction Box frame.

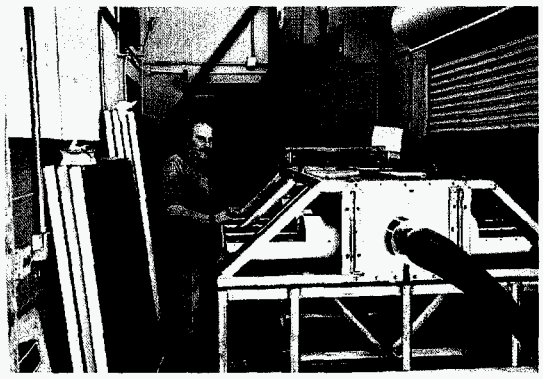

Figure 2 DUMAND Junction Box frame

Funding for the project was terminated shortly afterwards by the US DOE.

Now, if you do a short investigation (for example, a quick web-search) into DUMAND, that is about all the information you will find. That is a shame, because the project could be a source of lessons learned.

For example, the string laid at the end of 1993 was in fact recovered and repaired about a month later. But it failed again within a month, again because of a leak.

An attempt to repair it with an undersea robot a year later was not successful.

In fact, the DUMAND project started in 1976 and lasted altogether about 20 years. Ultimately, the reason DOE terminated it was that they grew exasperated after 20 years of ~~fumbling~~ progress. In the words of the SAGENAP committee report that closed the project, "The overall impression was that of a collaboration encountering a never-ending series of technical problems. As each was understood and fixed another seemed to arise." (SAGENAP, 1996)

While these words may seem harsh, and the DUMAND collaborators felt wounded by them, we shall see that there is perhaps a trend in ocean science, and we shall find we can apply these words elsewhere. Even, I regret to say, to my own project, NEPTUNE Power.

H2O

The Hawaii-2 Observatory (H2O) is a cable re-use project, aimed at doing ocean science. The engineering work is a collaboration involving the Woods Hole Oceanographic Institute and the University of Hawaii. The cable was an AT&T cable (of the pre-fiber-optic type) that had failed while in service between California and Hawaii. The installation site is at a depth of 5000 m, and is approximately at the midpoint of the old cable, see Figure 3. To install the observatory, in 1998, the cable was cut, and a device called a Termination Frame was added to the end that was still serviceable (the Hawaii end).

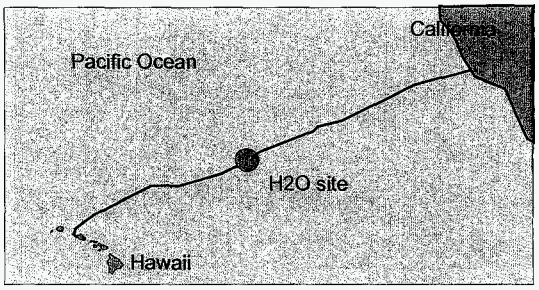

Figure 3 H2O site

During the process of lowering the termination into place, a support chain broke, and the communication cable and the termination fell to the ocean floor without restraint. You might be inclined to think that the word "plummet" would apply, but in fact for something the size and shape of the H2O termination frame (Figure 4) terminal velocity is around 1 m/s, so the equipment underwent a relatively slow descent. The frame landed (gently?) on top of a pile of cable, and was found to be still functional.

The Junction Box (for the science equipment) was then lowered and connected, and found to be functional. However, the system failed completely 12 hours later.

The good news was that the ship was still in the area, and was able to recover the Junction Box. Examination aboard the ship revealed the problem, and repairs were effected immediately. The Junction Box was reinstalled forthwith.

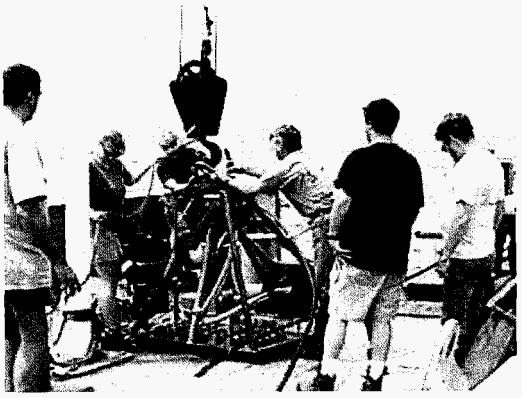

Figure 4 H2O Termination Frame deployment

This is not by any means the end of the story. The failure found is described on the H2O website and in various papers as "contaminated oil." (See, for example, Chave *et al,* 2005) And so it was. The oil was contaminated with a big blob of solder, causing a short circuit.

Within a couple of months of the installation, the seismic package failed due to a leak. When a ship was sent to replace it, the opportunity was taken to fix some of the other problems (with modems) at the same time as the seismic package.

However, even after this the system was never really up to expectations, and though H2O functioned partially for several years (and returned much data), a further visit was made in September 2003 to install an improved Junction Box and some additional experiments.

In the process, the power supply was found to be not operating correctly with the junction box, and repairs made on the ship did not appear to solve the problem. In addition, there was another "plummet" event: the Junction Box broke off the wire as it was being lowered to the bottom. The search for it on the ocean floor added three days to the deployment time. When eventually it was found and connected, half the power supply modules failed, so that power was available for only a fraction of the planned experiments.

The mission had more bad luck. A medical emergency required that the ship return to Hawaii, and this reduced the available time at sea. Because of time constraints, some of the science equipment was not deployed.

However, this turned out to be unimportant as a few days later, the H2O system stopped sending data. It seems that there may have been a fault to seawater in the power system.

NEPTUNE

The NEPTUNE project is a proposed scheme to place a large number of science nodes on the Juan de Fuca tectonic plate in the north-east Pacific. The sciences that could benefit from long-term measurements in this region of the ocean include those associated with tectonics, fisheries, water chemistry and more. The number of nodes to be installed has not been fixed at this point, but a number between 15 and 30 seems likely. Figure 5 shows one version of the proposed network.

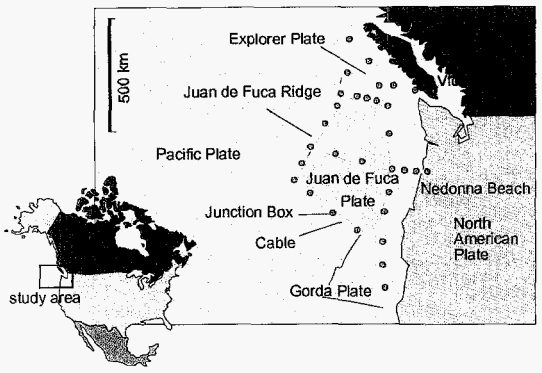

Figure 5 NEPTUNE Study Area

The NEPTUNE project plans to use a conventional subsea fiber optic cable and to bring power to the nodes by means of a parallel power system. A number of institutes are collaborating in the effort, and design work for the major subsystems has been divided among them. The Woods Hole Oceanographic Institute has the responsibility for developing a communication system. The Jet Propulsion Laboratory has had an overall management responsibility (now not funded), and responsibility for the power system. The University of Washington has responsibility for a good deal of the power work, and plays a major role in the effort to raise funds and coordinate the work. A group of collaborators in Canada has had responsibility for data archiving, though this, too, seems to be no longer funded.

Each of the groups was funded to do design work and fabricate prototype hardware. The first system to go in the water is going to be at the Monterey Bay Aquarium Research Institute, in a testbed they called MARS (for Monterey Accelerated Research System). While the various collaborators are going to produce hardware, it is not expected that they would make the hardware for the eventual NEPTUNE; rather they are doing proof-of-concept development.

In this review, I am going to focus mainly on the power aspects of the NEPTUNE project. (Until recently, I was the manager of the NEPTUNE Power Group.)

To make the power system work, a dc network was proposed that was in many ways similar to the ac networks that utilities use. It would be a parallel system, and power would be transmitted at a relatively high voltage, then stepped down for use.

The power for the science nodes would come from a dc/dc converter that would take the 10 kV on the cable and deliver 400 V to the user. (The power for the switches in the backbone would come from separate series or parallel power supplies of great simplicity, and therefore, it was hoped, great reliability.)

A new converter architecture was designed at JPL for the step down from 10 kV. Following software simulations, an engineering model of the converter was built that could operate at 3 kV. Following successful tests of this converter, the prototype 10 kV, 10 kW converter was built. One half of one of the two (redundant) converters built for the MARS testbed is seen in Figure 6, along with Dr Vatche Vorperian, the designer.

Figure 6 Prototype dc/dc converter assembly

This summer, following extensive tests of the various subsystems, the complete prototype converter was energized at 10 kV for the first time. The result was that the power source shut down, indicating a fault.

Reconsideration of the relationship between the converter and the power supply led us to conclude that there had been an inrush current on startup that was big enough for the supply to classify it as a fault. We reasoned that we could supply that inrush with a capacitor, and that in any case the capacitance of the ocean cable would solve the problem after installation. A capacitor of 10 μF (equivalent to the MARS cable capacitance) was added to the connection between the supply and the converter. Between the time taken to re-check the converter, to model the inrush, and to install the capacitor, a month elapsed.

When the converter was again energized, the inrush current was observed to be "ringing." The converter seemed to have a problem: noise was heard that indicated unusual behavior. We shut the system down. At autopsy, we found a few damaged components, though the main converter was still undamaged and operational.

As far as we can ascertain, the system exhibited unstable behavior during startup at 10 kV. No problem had been observed at 3 kV, and we had not expected an extrapolation of a factor of 3 to reveal anything new. In a paper written a few years ago, we had reviewed three known modes of instability (Kirkham *et al.*, 2003), and shown how we were addressing them. Here was what looked like a new mode of instability.

In fact, the instability we have seen *is* relatively new. A member of the Power Group (Shuai Lu, a graduate student at the University of Washington) found reference to something similar in a recent paper (Siri, 2000). The instability comes about because of interaction between the converter control system and the power supply current-limit characteristic. There are several solutions (change power supply, add damping, modify converter control system) and we are now investigating the options.

Unfortunately, it has been now about 3 months since the converter was last energized, and the project has exhausted its funds.

THE LESSONS

Engineers generally enjoy challenges, but in the case of the engineering for the ocean science applications, it is the challenges that have triumphed, at least to some extent. It is not enough to do *some* hard stuff – you have to do *all* the hard stuff.

This is a question of *culture.* In order to succeed, the ocean science community must adopt better methods of system engineering and mission assurance, and better methods of engineering for a long life.

The need for system engineering is obvious. The kind of observatories that are being planned involve a number of subsystems acting as one system. The bookkeeping methods of system engineering as well as the technical aspects are crucial to success.

The mission assurance needs are perhaps less obvious. Mission assurance plays a role in almost all manufacturing efforts. The makers of cars make cost-effective use of materials, for example, to hold down costs without compromising safety. So do the makers of airplanes, though the numbers are so different that the equations have different solutions.

Mission assurance work is familiar, too, to the space exploration community that I come from, and to the submarine cable community. These various concepts that together make up mission assurance should become familiar to the world of ocean science, both at the engineering level and the sponsor level, if the ultimate users of large observatories – the scientists – are to succeed.

And what does this difference of culture arise from? Why are the methods and approaches of the different cultures different? In a word, *economics.*

Economics is the way two opposing trends get resolved: the customer wants cheap goods, the manufacturer wants a profit – as a result there is economic pressure for efficient manufacture and distribution, and for comparison shopping. In the world of government-sponsored research, the engineers and scientists always want more funding, and the sponsors are budget constrained. As a result, there is an economic pressure to make the available resources stretch as far as possible.

In the US, the economic equation of ocean science has been distorted by the way ship time has been made available. A number of agencies as well as the National Science Foundation support a fleet of 27 ships known as the UNOLS fleet, for University National Oceanographic Laboratory System. As far as I can tell, the fleet is available at no cost or at greatly subsidized cost to ocean researchers.

The result is that equipment is sometimes sent to sea before it is ready, and sometimes deployed before it is fully tested. The National Science Foundation understands that doing ocean science is difficult, and they forgive the occasional failure.

The space community knows that doing space science is difficult, but it also knows that equipment that is not thoroughly tested and debugged might fail after all opportunity for repair has passed. (Think of the Hubble Space Telescope.) The subsea telecommunications people know that doing ocean-bottom cables is difficult, but they also know that sending a ship to make repairs to a cable that has been deployed is extremely expensive, and it is more sensible to spend the money making sure a repair ship is not needed.

Ocean scientists and their engineering colleagues are not typically in this mode. Both DUMAND and H2O have shown considerable skill and ingenuity in building quality systems and stretching the resources. Yet the effort has not avoided the need for repeat ship visits to make repairs. The NEPTUNE power project, still pre-deployment, was planned in a "success-oriented mode," and insufficiently funded to complete lab tests prior to deployment.

The attitude that allows this kind of event begins at the top: the government sponsors accept the occasional failure as the price of doing difficult work *rather than paying the price of more rigorous development*. The attitude extends to project management, who are accustomed to few reviews and insufficient testing.

Thus project management support, which is needed for system engineering and mission assurance, or reliability engineering, is often not forthcoming. The maintenance costs go up, even as the initial costs are trimmed.

I am convinced that with the appropriate level of effort in system engineering and engineering for reliability, a subsea observatory can be designed with acceptable initial cost and acceptable requirements for maintenance. By examining and trading off architectures and designs in the light of reliability engineering, an orderly progress to a successful observatory is made more likely. The design approach, fabrication techniques, functional and environmental testing, handling and deployment are all affected. At times the process may seem overwhelming, but experience in the deepest water and the furthest reaches of space underscore the benefits.

The sponsors' expectations must be "adjusted" until they are in line with this reality. Sponsors must expect to fund a management system that provides an environment in which *reporting* is routine, *reviews* are expected, and *configuration management* is strict. But system developers cannot work in a vacuum: unless the *system requirements* are carefully spelled out (and reviewed and fixed) early on (a process that must involve the scientists), subsystem performance runs the risk of far exceeding needs, or (worse) of not meeting them.

Speaking of reporting, I would like to point out that it is useful to document failures as well as successes. Not all our work proceeds as planned: those who follow can benefit from our exploring dead-ends, and even from our mistakes. As George Santayana famously wrote, "Those who cannot remember the past are condemned to repeat it." (Santayana, 1905)

The design and construction of an ocean observatory is engineering, not science, though scientists must be major participants in the work. But engineering management is needed. If you read the SAGENAP report, you see that this is the aspect of DUMAND most criticized.

One way to inculcate an appropriate management approach into ocean science would be to adopt the techniques used for spacecraft development. Better yet, copy the methods of the ocean telecommunications community. There will be costs: the hardware will cost more because its component parts will have to be *qualified* for the intended use. (Now we are back to the Boeing 737 that introduced this paper.) The development process will cost more because there will be additional documentation and additional reviews and additional tests to perform.

Considerable resources will be required for *mission assurance.* Included in the overall discipline of MA (sometimes called QA, quality assurance) are factors such as in-process manufacturing inspections, material evaluations and more. And of course, many design issues. It is axiomatic that you cannot *test* reliability into a piece of hardware or software. It has to be designed in by appropriate choice of parts, derating, use of redundancy and so on. Books have been written on each of these: for a short overview, and a list of references you might look at a recent paper on the topic for the cable-reuse community (Bowerman *et al.*, 2003).

WRAP-UP

I offer the following suggestions:

- Allow the engineering effort to be managed by someone with a strong background in commercial submarine systems. Accept the increased burden of management, reporting, and testing.
- Keep the sponsor realistically informed of the likely costs. But concentrate on lifetime costs, not just costs up to deployment.
- Don't conclude that you have an optimum design until you have done some trade-offs of alternatives. In a field where no-one has a lot of experience, one's instinct for solutions may mislead. This is part of system engineering.
- While you might want to minimize the amount of new technology, some development effort may be justified. Be careful how you plan, if it is in the critical path.
- Believe in the long-term benefits of mission assurance. Though the overhead work and the initial costs will be higher than you may be used to, the long term results will pay back the early investment. (Consider the performance of the two rovers now active on Mars.)
- Establish an internal "Lessons Learned" system so that you can, as a collaboration, remember the past and avoid repeating it.

and finally:

- Double the first cost estimates to come from the engineers. We engineers are all optimists.

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Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government, the University of Washington, or the Jet Propulsion Laboratory, California Institute of Technology.

To whom it may concern:

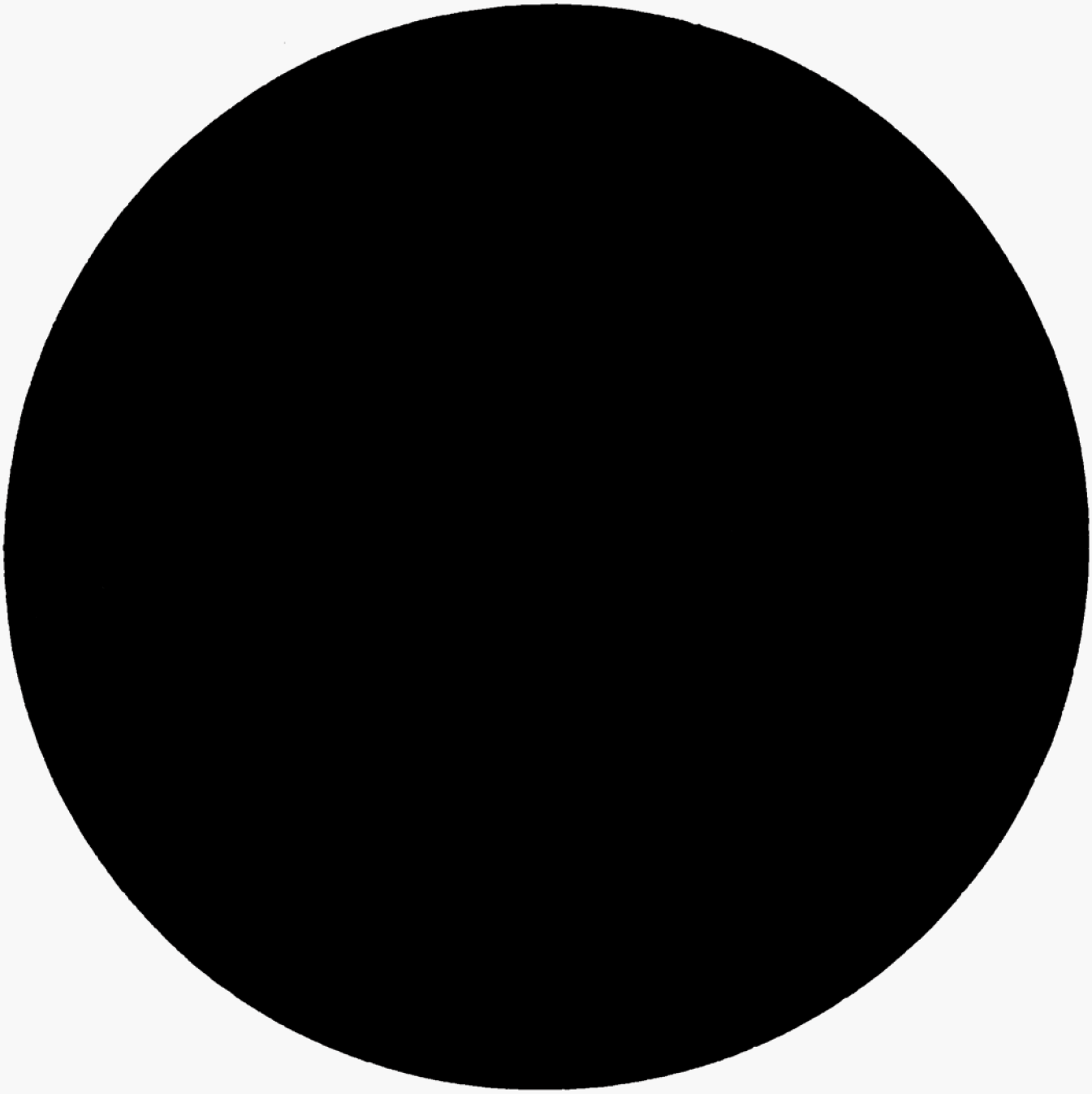
This paper contains no research results, no science, and no new technology. It is just *opinion* on the managing of sub-sea engineering.

Does it really need an Acknowledgment statement?

If so, it seems off-target to say "The research described was performed . . . ." Can I modify the one in the paper to read as follows:

> The writing of this paper was done at the Jet Propulsion Laboratory, California Institute of Technology, and was sponsored by the University of Washington through an agreement with the National Aeronautics and Space Administration.
>
> Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government, the University of Washington, or the Jet Propulsion Laboratory, California Institute of Technology.

The first seven words are what is different. (Some years ago, Mike Keller at Caltech generated some words like that for a situation where the work had been done outside of JPL, and only the writing of the paper had been done here.)

–Harold

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