John Swallow's pinger circuit – a foray into 1940s and 50s electronic archaeology

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1. Background

Over recent years JG made a number of visits to the historic ship, *Medusa*, now based at Gosport. *HMS Medusa* was a harbour defence motor launch (HDML), a wooden hulled vessel built and launched in Poole, Dorset in 1943. http://www.hmsmedusa.org.uk/ . *HMS Medusa* ended her working life as one of the Admiralty Hydrographic Department's inshore survey vessels (1953 - 1968) commanded at various times by Roger Morris who became Hydrographer of the Navy and by Desmond Scott who became Executive Secretary of the Intergovernmental Oceanographic Commission of UNESCO.

My interest was aroused by *Medusa's* role in D-Day. The invasion fleet had to be guided through gaps that had been swept in the minefield laid down the centre of the English Channel. These gaps were marked before D-Day by acoustic beacons anchored to the sea bed (Operation Enthrone) and *Medusa*'s role was to home in on one of the beacons and sit over it as a visible marker to guide the invasion fleet – a bit like things that we oceanographers do, but under much more dangerous conditions.

So that set me thinking: What kind of a beacon was it? And, Did the 10kHz pingers that we used (starting with John Swallow's floats in 1954/5 and Tony Laughton's deep-sea cameras) owe anything in their design to the WWII beacon?

The *Medusa* web site describes the beacon as an FH830 and a Google search revealed that it was designed by a Canadian, George Whalley (1915-1983), a member of the Royal Canadian Navy Volunteer Reserve who, post war, was best known as a broadcaster and poet. (http://archives.algomau.ca/gwp/node/62).

My first enquiry was with Nigel Godsell who maintains a web site similar to OceansWormley but devoted to the work of the Admiralty Research Laboratory in the hope that he may have known of a link between the WWII pingers and the NIO ones when Group W was at Teddington. He did not know of one but we had an interesting discussion about nickel scroll transducers. I sent him a photo of the transducer on John Swallow's float and he sent me a photo of one that was much larger. (Figure 1)

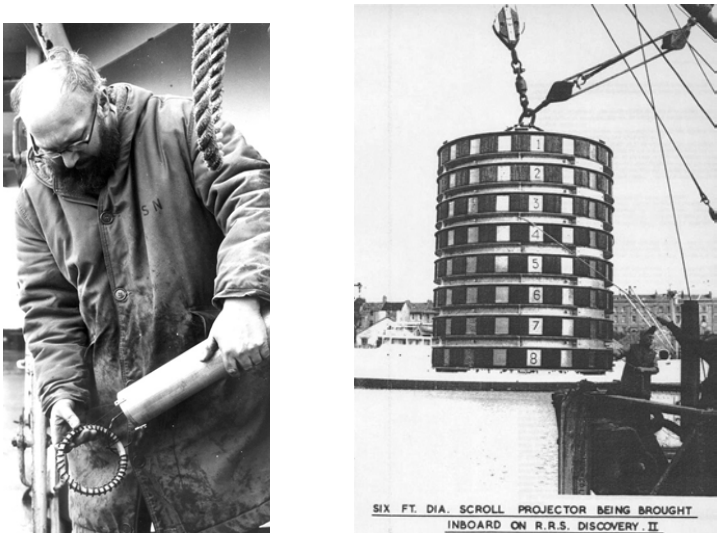

Figure 1. **Left** *John Swallow deploying one of his floats in the Irminger Sea in 1962 (Courtesy WHOI archives)* **Right** *A 6' diameter nickel scroll transducer from ARL being brought aboard RRS Discovery II. (Courtesy Nigel Godsell).*

So what of FH830? I later discovered that the handbook and design details are held in the National Archives and obtained scans and similar copies from Alan Watson at the Medusa Trust.

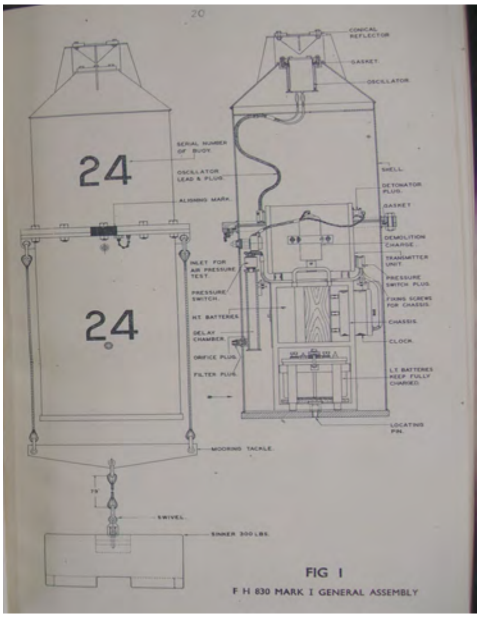

FIG I

F H 830 MARK I GENERAL ASSEMBLY

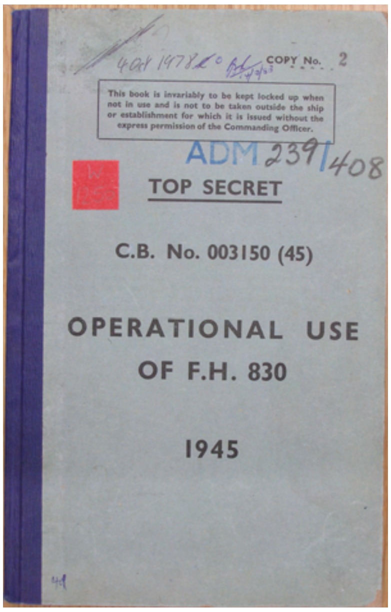

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Figure 2 *Schematic of the FH830 acoustic beacon and the cover of a later Admiralty handbook (Courtesy of National Archives, Kew)*

What was immediately clear was that there was no real link between FH380 and the NIO design. FH830 used a quartz crystal transducer working at 20 kHz and linked to a conical projector to direct the acoustic signal upwards.

At various times I involved Gwyn in my FH830 discussions and this sparked his interest. He wondered; Could he build replicas of the FH830 and Swallow circuits? and How would they perform? Here is his part of the story

2. Dr. John Swallow's 1955 acoustic pinger

John Swallow's seminal 1955 paper[1] on his neutral buoyancy float contains the circuit diagram of its acoustic pinger. The circuit was designed by Rick Hubbard, a technical assistant within Group W at Teddington (Figure 3). Hubbard did not move down to Wormley[2]. The circuit is reproduced here as an inset in Figure 4 which also shows a photograph of the component layout and the acoustic transducer. There is an elegant simplicity in its design, summarised in a single sentence in Swallow's paper, "*The transmitter consists of a nickel scroll resonant at 10 kc/s, wound toroidally and energized by discharging a capacitor through a flash tube*".

Figure 3 *Admiralty Research Laboratory Group W 1952. Rick Hubbard, back row left alongside D.W. (Dick) Privett, later NIO Librarian, In front are Henry Charnock (L) and George Deacon. NIO/IOS Directors. (Courtesy NOL archives)*

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[1] Swallow, J.C., 1955. A neutral-buoyancy float for measuring deep currents. Deep Sea Research, 3: 74-81.

[2] Our thanks to Brian McCartney for this information, 16 October 2018.

The type of flash tube in this circuit had a history going back to the 1920s with the invention of the gas-filled thyratron as a high current triggered switch. The device was made smaller, more robust, and less expensive due to the work of Dr. Harold "Doc" Edgerton at MIT in the early 1930s. His fascinating diaries are also available online; for instance on 6 May 1931 he describes a mains-powered circuit for a flash tube stroboscope using a circuit[3] not too dissimilar to that of Hubbard. His tube became known as the strobotron. Edgerton also made seminal contributions to the development of sonar, and cofounded the company Edgerton, Germeshausen, and Grier that became EG&G in 1947. EG&G's Marine Instruments subsidiary developed a wide suite of oceanographic equipment including sidescan sonars, acoustic releases and vector averaging current meters that were used at Wormley.

Let's look at the pinger circuit in detail, drawing on John Swallow's notes from his diary[4] and illustrated with oscilloscope measurements made on a replica constructed in 2018,

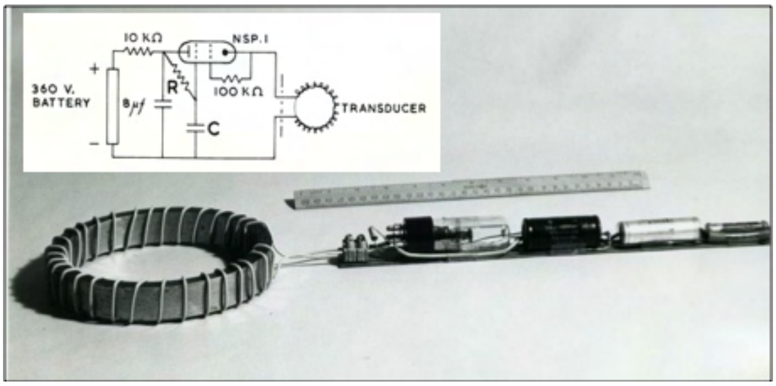

Figure 4. *The six electronic components and the nickel scroll transducer that made up the 1955 acoustic pinger used in John Swallow's neutral-buoyancy float together with the circuit diagram. Source: National Oceanographic Library 4152 (Circuit), 4160 (Components).*

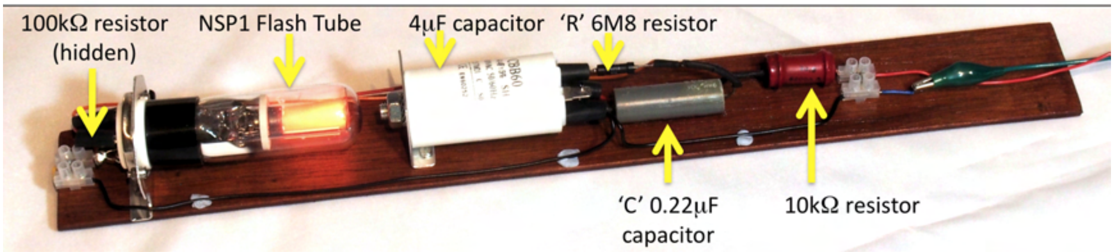

Figure 5. *The circuit of Figure 4, without the transducer, as constructed in 2018 using the same type of flash tube and similar components to the original. While period resistors have been used the capacitors are modern, as 1950s capacitors of this type will have a high leakage current.*

2.1 How the pinger works

The 360V battery charges the 8μF reservoir capacitor via a 10kΩ current-limiting resistor in about 0.2s, the maximum current drawn from the battery being about 36mA. Resistor **R** and timing capacitor **C** determine the ping repetition rate. The NSP1 flash tube is a cold-cathode "Neostron" with four electrodes[5]. It passes no current until the voltage at the trigger electrode (connected to **RC**) rises to a tube and age-dependent value of between 80 and 130V. At the instant of triggering an arc forms from the positive anode at the top of the tube to the cathode near the base. The peak current can be 200A. In practice the current is limited by the resistance of the wiring, the internal resistance of the reservoir capacitor and the inductance of the transducer. Typically, the current pulse may last for 10μs.

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[3] See https://edgerton-digital-collections.org/notebooks/03 on pages 88 to 90

[4] Available at https://viewer.soton.ac.uk/nol/fullscreen/2417/1/

[5] Details and data sheet available at: http://www.r-type.org/exhib/aaa0473.htm

The current pulse, flowing through the coil wound through the nickel ring, induces a magnetic field that causes the ring to change its circumference - nickel being a magnetostrictive material. A simple analogy is that of tapping a bell or a glass - the impulse gives rise to a "ringing" at the resonant frequency of the physical item - be it a bell, a glass or in this case the ring of nickel. Following the impulse, the duration of the ringing is determined by the amount of damping, be it within the nickel ring, from the wire wound over the nickel or from the surrounding water. The transmission frequency of 10kHz and the pulse duration are therefore determined by dimensions and physical properties and not by the electronics.

2.2 John Swallow's September 1955 tests on the electronics

Swallow's diary describes a series of tests on a number of pingers prior to a deployment. His notes show a complete understanding of the circuit and likely sources of problems, not surprising given his training in electronics while at the University of Cambridge in 1941–43, followed by training in the repair and maintenance of radio equipment at the Admiralty Signals Establishment, Lythe Hill, Haslemere in 1943–44 and his tour of duty attached to the Royal Navy in Ceylon in 1944–46[6]. He examined the:

- ***Optimum number of turns on the transducer***: Through experiment the optimum number of turns on the transducer was found to be 30 from measuring the signal received on a similar transducer over a short path in water, having noticed that his early, peculiar, results were affected by air bubbles trapped on the transducer face.
- ***Lifetime of the flash tube***: Swallow checked that the ~144,000 flashes over a four day deployment at one every 2-3 seconds was a very small fraction (0.27%) of the expected life of the flash tube, given as 300 hours at 50 pulses per second in the datasheet. However, the projected life was not being achieved in practice. Of six pingers he tested on 3 September 1955 three had problems with their flash tubes: not triggering, giving a continuous faint glow and taking longer than calculated to trigger, and not starting "*except when tapped*".
While the circuit as published (Figure 4) showed the flash tube as the commercial Ferranti NSP1, Swallow actually used the military equivalent, the CV220[7]. It is this data sheet that has the expected lifetime. However, it does not contain a warning (present in the 1957 NSP1 data sheet[5]) on the permanent damage that could occur if the tube was run with too low a discharge current (of 5A or less). Low currents result in a continuous glow rather than a flash, leading to damage from excessive heat dissipation. Possibly some of his tubes had been run with too low a current at some time in their life.
- ***'0V' connection of the timing capacitor***: By 5 September another tube had stopped flashing. Swallow determined that one cause could be a "*voltage surge*" caused by having the timing capacitor **C** connected to the '0V' end of the transducer coil, as in the circuit diagram. He modified the circuit on all the pingers by moving the timing capacitor '0V' connection to the cathode of the flash tube. All were working fine into the following day and there are no further notes on problems with the flash tubes.
- ***Battery life***: The 360V supply was built from 24 Siemens S123 hearing aid batteries, each battery weighing $1^3/_8$ ounces[8], for a total battery weight of about 1.07kg. From 26 October to 5 November 1955 Swallow had two pingers on test to determine the life of their batteries. One unit had an 8μF reservoir capacitor and began at 29 pulses per minute, the other had a 4μF capacitor and began at 19 pulses per minute. Figure 6 shows his results for Unit No. 12 with the 8μF capacitor starting with fresh "*Battery No. 2*". The graph also shows our calculation for the cumulative energy extracted, comprising the energy stored in the capacitors and that dissipated in the series resistors during charging; the 85.5kJ is equivalent

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[6] From typed notes of a conversation between John Swallow and Margaret Deacon 30 November 1994.

[7] Data sheet available at: http://www.r-type.org/pdfs/cv220.pdf

[8] https://viewer.soton.ac.uk/nol/fullscreen/2417/20/

to 135mAh. Swallow used these figures to estimate that the batteries would give a pinger with a 4μF capacitor starting at 20 pulses per minute a lifetime of about 10 days.

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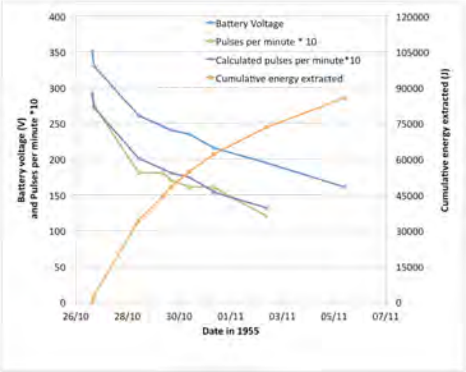


Figure 6. *Voltage and pulses per minute during a battery lifetime test by John Swallow during October-November 1955 together with our calculation of cumulative energy extracted and expected pulse rate.*

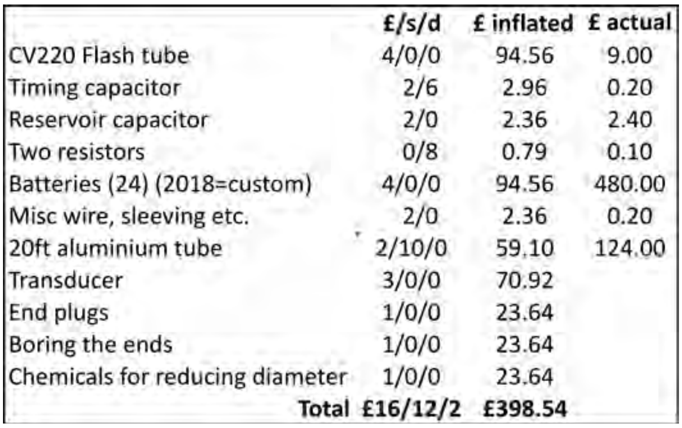
- ***Variation in pulse rate***: One of the limitations with this simple circuit is that the inevitable decay of the battery voltage has a substantial effect on the pulse rate. Assuming a fixed trigger voltage *vt*, and a battery voltage of *vb* the time between pulses is given by:

  -ln(((*vb*-*vt*)/*vb*)^CR)

with *vt* at 110V the calculated change in pulse rate in Figure 6 closely matches that observed by Swallow. Later pingers used crystal-controlled pulse timing circuits that enabled visual pulse-to-pulse correlation on wet-paper recorders such as the Mufax, impossible with this simple circuit.

2.3 Cost of the 1955 pinger and today's equivalent

The total cost of components for a simple pinger float in 1955 was about £17. John Swallow's diary gave the costs of individual parts, as shown in this table. We've added the costs in 2017 using a figure for inflation together with today's actual prices where available for each item. The flash tube is still available as "New Old Stock" from specialist suppliers, and is a real bargain compared with the 1955 cost. The other electronic components are either a similar price or cheaper in real terms while the aluminium tubes are more expensive and the batteries especially so. For the batteries we've listed exact equivalents that are available today from suppliers that make replicas. A modern, cheaper solution would be to use standard alkaline cells in a 12-volt pack and use a solid-state DC-to-DC step up converter to give the 360V.



	£/s/d	£ inflated	£ actual
CV220 Flash tube	4/0/0	94.56	9.00
Timing capacitor	2/6	2.96	0.20
Reservoir capacitor	2/0	2.36	2.40
Two resistors	0/8	0.79	0.10
Batteries (24) (2018=custom)	4/0/0	94.56	480.00
Misc wire, sleeving etc.	2/0	2.36	0.20
20ft aluminium tube	2/10/0	59.10	124.00
Transducer	3/0/0	70.92	
End plugs	1/0/0	23.64	
Boring the ends	1/0/0	23.64	
Chemicals for reducing diameter	1/0/0	23.64	
Total	£16/12/2	£398.54	

2.4 Waveforms as seen on the modern replica

These three screen captures from an oscilloscope for the modern replica illustrate the working of the Swallow pinger as described in the text above. The first two cover a time span of 2.4 seconds.

Figure 7 shows the rapid discharge of the 4μF reservoir capacitor followed by recharging to 300V in about 100ms. Figure 8 is the voltage at the flash tube's trigger electrode. The sharp decrease to zero happens as the flash fires, the voltage then rises as capacitor C charges through timing resistor R until it reaches the trigger voltage at which the cycle repeats. Here the interval is 660ms, shorter than Swallow would have used. Figure 9 represents the current through the flash tube; the trace covers 24 μs and shows a complex waveform with the main discharge happening 3μs after the initial trigger. It is this large current pulse, with its very fast leading edge, that excites the magnetostrictive transducer at its own resonant frequency.

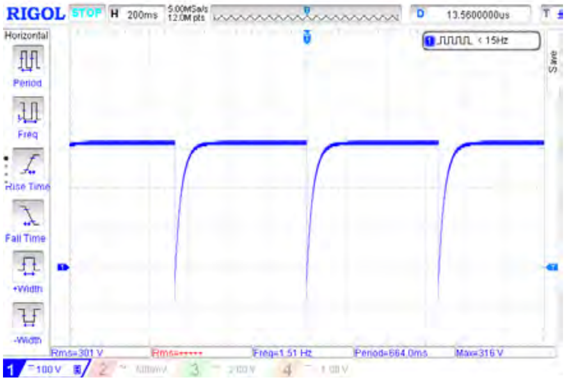


Figure 7. *Voltage waveform at the reservoir capacitor. 200ms and 100V per division.*

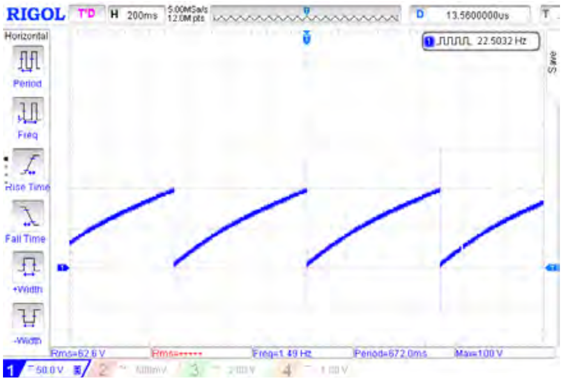


Figure 8 *Voltage waveform at the trigger electrode. 200ms and 50V per division.*

Figure 9. *Current waveform at the flash tube output. 2μs per division, current scale not calibrated..*

3. **George Whalley**'s **WWII FH830 acoustic pinger**

The acoustic pinger within the FH830 sub-surface Marker Buoy designed by George Whalley at the Admiralty in the early years of World War II was different in every respect from John Swallow's 1955 pinger.

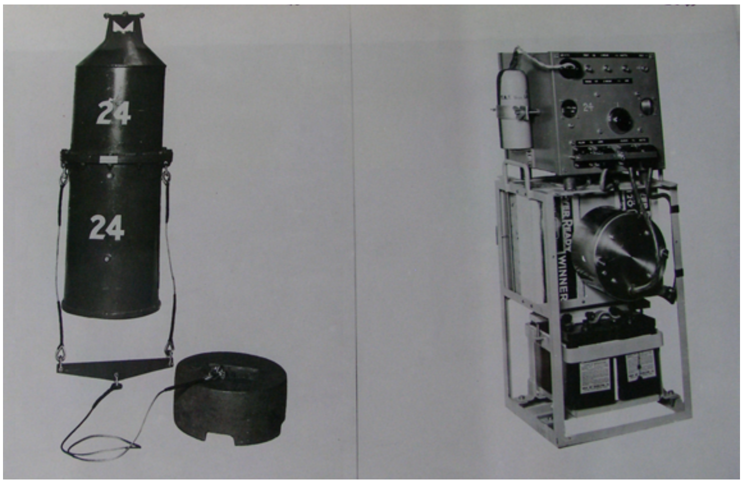


Figure 10. *FH380 Mk 1 acoustic beacon (L) and it associated transmitter unit. (From B=National Archives Courtesy of the Medusa Trust)*

The following table sets out how each circuit fulfilled the essential functions of an acoustic pinger and the component technologies. Most of the information in this table on the FH830 pinger was obtained from document ADM 277/28 in the UK National Archives[9].

Function	Whalley, WWII FH830	Hubbard and Swallow, 1955
Transmission frequency	Vacuum tube (valve) inductor-capacitor tuned circuit. Nominal frequency 20kHz.	Mechanical resonance of nickel strip wound as a tight scroll to form a ring. Nominal frequency 10kHz.
Ping interval	Charging of capacitors via a resistor driven by the transmission signal with switch-selected periods. "*Slightly affected*" by the battery voltage.	Charging of a capacitor via a resistor from the high voltage battery. Interval increases markedly as battery voltage decays.
Ping duration	Set by capacitors, valve grid current and the cut-off voltage and mutual conductance of the oscillator valve, typically 100ms.	Set by the mechanical damping of the oscillations of the nickel scroll, typically a few milliseconds.
Acoustic transducer	Piezoelectric, quartz crystal. High impedance, about 1Mohm in parallel with 295pF, voltage driven, about 1400V peak.	Magnetostrictive, nickel scroll. Low impedance of a few ohms, current driven, about 50A peak.
Active devices	Two directly heated vacuum tubes (valves) requiring 4v filament batteries, one as the oscillator, and the other as the output amplifier.	Single cold cathode flash tube requiring no filament supply.
Circuit complexity	Twenty-two components, two specially wound autotransformers in the Mk1 pinger, excluding timer circuitry.	Five components, none specially made.

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[9] "*ASDIC beacon buoy. Includes 6 photographs depicting: Asdic beacon buoys: FH 830, …*", catalogue entry at http://discovery.nationalarchives.gov.uk/details/r/C527364

Maximum depth	25 fathoms (about 46 metres)	Tested to 4500 metres.
Endurance	Up to 85 days	About 10 days.
Batteries	Low voltage: MK1Four Varley V80 2V lead acid accumulators in series parallel, weight about 24kg total[10]. MkII and III used six Siemens N size dry cells in series parallel. High voltage: Three Ever Ready Winner 120V dry batteries in series, weight 9.9kg total. Total battery weight about 34kg.	High voltage: 24 Siemens S123 hearing aid batteries. Total weight about 1.07kg.
Total weight of buoy / float in air.	278lb (126kg)	About 10kg.

3.1 How the pinger works - oscillator

The pinger circuit in Figure 11 has been transcribed from that in Figure 4 of the "*Extract from the F.H. 830 Mk. I Operating and Maintenance Instruction Book*" in the National Archives[9]. The resonant frequency of tapped coil L2 with fixed capacitor C10 and variable capacitor C2 sets the transmission frequency. C2 provides a variation of about 200Hz around 20kHz. Oscillation is maintained by the amplification provided by V1 with the feedback provided by coupling capacitor C8.

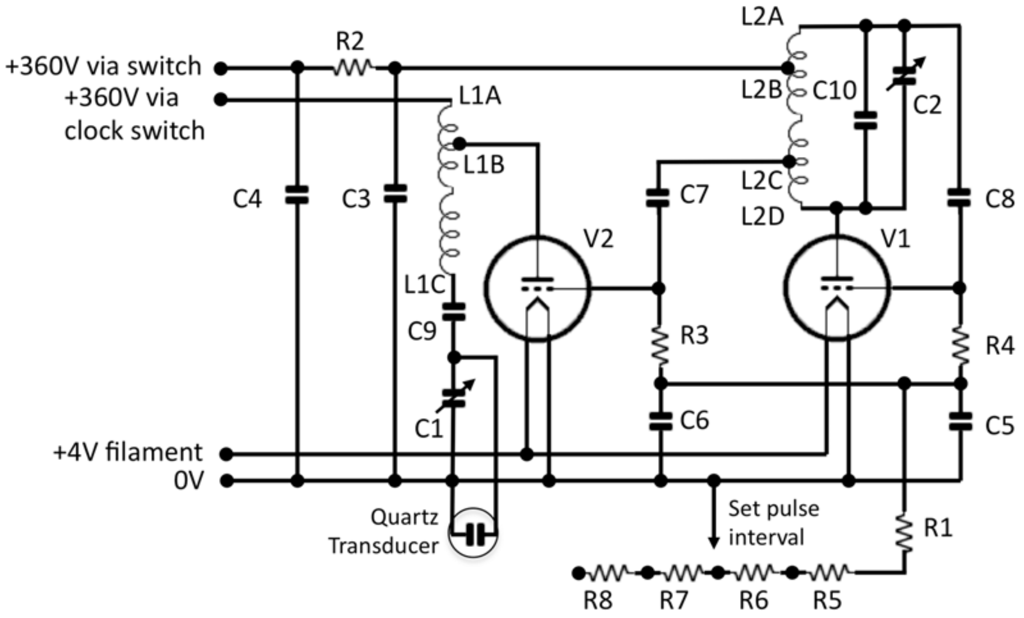

Figure 11 *Diagram of the pinger part of the FH830 buoy circuit, redrawn from the original.*

In a conventional oscillator the lower connection of bias resistors R4 and R3 would be directly to the common negative of the filament and high voltage supply (which we will call ground). However, here the connection is via the resistor chain R1 and R5-R8, in parallel with capacitors C5 and C6. This arrangement sets both the transmission pulse duration and the pulse interval. When the circuit is switched on the lower connections of R3 and R4 are at ground voltage, as the circuit oscillates the grid and filament of the each valve act as diodes, rectifying part of the AC waveform, and a negative DC voltage builds up at the grid. The potential difference across R4 drives a current

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[10] No details were given, and none could be found, for the Varley accumulators. To give an indication of weight and capacity dimensions from the drawings were scaled by the buoy outside diameter of 16", to give a size of about 5"x5"x7.25". The closest 2V accumulator capacity and weight, typical of period, were then obtained from http://www.valve-radio.co.uk/literature/oldham-accumulators-and-batteries/
High voltage battery details from https://www.radiomuseum.org/r/ever_winner_120.html

through it, charging the capacitors C5 and C6, with a small fraction through the high value resistor chain R1, R5-8. With a time constant determined by the product of R3 in parallel with R4, and C5 in parallel with C6, the voltage at the V1 grid becomes more negative until it reaches the cut-off voltage and the transmission pulse ends. Cut-off is the negative grid voltage at which no current flows through the valve. The discharge path for C5 and C6 is through the resistor chain R1, R5-R8, which sets the pulse interval. Oscillations do not immediately restart as the capacitors discharge as the gain of the valve will be very low close to the cut-off point and a greater gain is needed to start oscillations compared with maintaining oscillation once started. The amount of gain needed is mainly determined by the turns ratio between taps L2B and L2D and L2B and L2A, L2B being at AC ground due to C3; the handbook does not include this detail.

With R3=51kΩ and R4=100kΩ and C5=2μF and C6=1μF the time constant CR, and hence the approximate pulse duration, is 102ms. The operator can set the pulse interval via a plug connection to the ends of R5-8, which gave time constants of 1.35, 2.88, 5.88 and 13.8 seconds. However, as V1 begins to oscillate after about 0.34 of a time constant the approximate pulse intervals were 0.5, 1, 2 and 4 seconds.

3.2 How the pinger works - amplifier

Tapping L1C provides an impedance match from the oscillator tuned circuit to the grid of the amplifier V2 via coupling capacitor C7. The amplified signal at V2 anode is tapped into the tuned autotransformer L1 at L1B, with the high impedance quartz transducer connected at tap L2C via coupling capacitor C9. Variable capacitor C1 is in parallel with the quartz transducer and serves to tune L1 to parallel resonance.

Somewhat confusingly the circuit diagram and the text refer to the quartz transducer as the "oscillator", which, at least these days, suggests that the quartz transducer sets the oscillation frequency. That is not so, L2 and the capacitors in parallel set the frequency.

Both the amplifier and oscillator valves are type P410, directly heated audio output triodes[11] that were introduced in 1929. While the DC voltage at the anode of V1 is reduced by the product of R2 and the current flowing through it, the full battery voltage, initially 360V, is present at the anode of V2. This far exceeds the "absolute maximum" of 150V in the P410's data sheet and shows the robustness of these 1920s triodes.

Overall, this pinger has a clever method of providing a pulsed transmission with a user-settable pulse interval in a compact design that uses standard components, and it would have been common practice to wind inductors for specific requirements.

3.3 Waveforms as seen on a modern functional replica

A functional replica of the FH830 circuit in Figure 11 has been constructed with components of varying vintage, Figure 9. While capacitors from the 1940s are available they would not be appropriate for use in this circuit due to inevitable leakage currents exceeding 1μA that would affect the timing circuits and the valve biasing. Resistors from the 1940s have been used. P410 valves are now very scarce, and when available they cost about £100 each. Valves with 2V filaments were more common and are less expensive. This replica uses two PM2 audio output triodes dating from the late 1920s.

The FH830 handbook does not provide details of the two autotransformers other than the inductance of the complete windings, 15.5mH for the oscillator and 160mH for the output. Here, the coils have been wound on ferrite cores that were introduced in 1949[12], with the tapping points calculated to match the circuit impedances and, for the oscillator, to provide sufficient feedback given the amplification available from the PM2 valve.

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[11] See http://www.r-type.org/exhib/aaa1263.htm

[12] The 1949 example in Figure 2 at https://ieeexplore.ieee.org/document/4490128

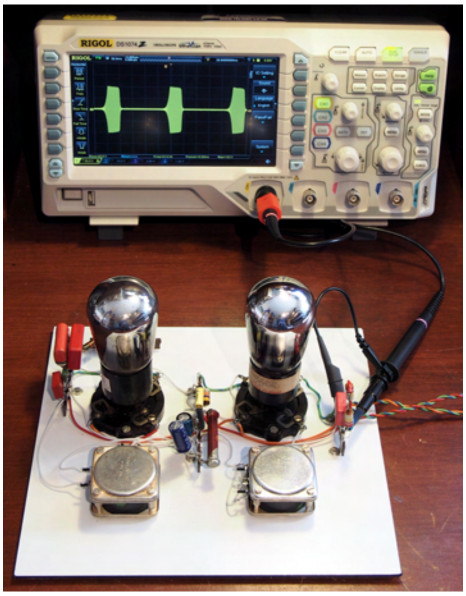

Figure 12 *The functional replica, constructed to the original circuit diagram but with components of varying vintage.*

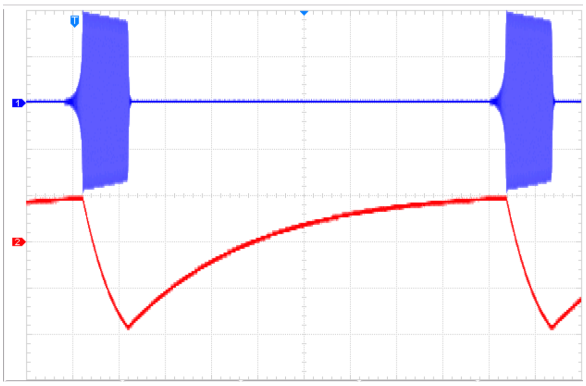

Figure 13 *Upper trace: Output voltage across a 440kΩ dummy load showing a pulse duration of about 60ms and a pulse interval of about 460ms (Y-axis: 200V per division, X-axis: 50ms per division). Lower trace: Voltage at the junction of R4 and C5; the mean level is -21V (Y-axis: 1V per division).*

The upper trace in Figure 13 shows a pulse output of 800V peak to peak across a 440kΩ dummy load at a supply voltage of 120V. Given the valves are 90 years old they have not been pushed to 360V as in the FH830. The pulse length at 60ms is shorter than the 100ms in the handbook. However, the following Table shows that pulse length is dependent on supply voltage, and could conceivably reach 100ms at 360V. The pulse interval is also shorter than in the handbook, here the setting was for 1 second but the interval was about 455ms at 120V. There is less of a variation for the pulse interval with the applied voltage, far less than for the Swallow circuit, a useful feature. However, pulse length and interval do depend on individual valve characteristics, swapping the oscillator and amplifier valves halved both times. The lower trace in Figure 13 shows the voltage at the junction of R4 and C5 where the mean level was -21V. Here the grid is driven more negative during the pulse as C5 and C6 charge up until the valve cuts off and transmission stops. This point then becomes less negative, and when the hysteresis to restart oscillation is overcome, and the gain increases, the circuit begins to oscillate. The slow rise and gradual decay that are characteristic of this circuit are shown more clearly in the expanded view in Figure 14.

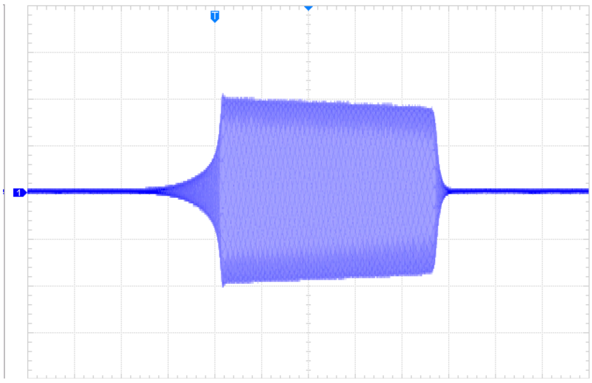

Figure 14: *Expanded time trace for the output pulse showing the slow initial rise and the gradual decay (X-axis: 10ms per division).*

High voltage supply (V)	**Pulse interval (ms)**	**Pulse length (ms)**	**Peak voltage (V)**
45	365	40	144
60	410	45	200
90	435	50	304
120	455	60	408
150	430	70	464
175	430	75	520

4. Postscript and a tribute

This is as far as we have been able to progress. The major stumbling block has been that we have been unable to locate transducers of the types use in 1944 and from 1955 onwards to test the acoustic output of these pingers.

Those of us who worked with Swallow's floats in the 1950s and 60s can vouch for the challenge of locating his floats even when working under good acoustic conditions and from a quiet research ship.

It increases our admiration for the anonymous ASDIC operator aboard HMS Medusa on D-Day who ensured that the beacon was located and that the vessel remained on station! He must have been one of the most important unsung heroes of the day.

Acknowledgement
We are grateful to the National Oceanographic Library for permission to quote from John Swallow's 1955 diary and to reproduce the two photographs NOL4152 and NOL4160.