The Edge Series Two
Bottling The Sun

TC	Pictures	Audio
00.00	TITLES	MUSIC
0.22	Glossy intro shots	Commentary
		In the middle of the twentieth century, science made a promise which it has yet to keep.
0.35		Commentary
		Limitless energy from the thermonuclear reaction which powers the sun.
0.41		Commentary
		It's called fusion.
0.48		Commentary
		Thousands of scientists have worked on this project. To make a fusion machine and power the world.
0.54	Title "Bottling The Sun"	MUSIC
1.01		Commentary
		This is a reunion for a team of scientists and engineers who made one important step forward towards the future of energy.
1.13	Alan driving	Alan Sykes
		The whole idea that a scientist could improve the lot of mankind by scientific research, and getting a new source of power, the concept it seemed very important and it’s even more important now.

1.26	Alan driving, then by START	Alan Sykes The very fact that it is very difficult to do, and is still some years off, is, is part of the challenge and it's (er) a matter of solving bits of a detective story, finding out what the solution to all these problems are. First of all finding what the problems are and then proposing better solutions, and then checking them out.
1.48	London street	Commentary We need fusion because society is addicted to electricity.
1.56	Reunion, POV driving through London, INT cab	John Chesshire All of our modern economies are very energy dependent; we are almost hooked on the stuff. Everything we do, we drive, we travel, we cook, we want energy available, when we want it, so it needs to be reliable at a cheap and affordable price. And this is one of the hopes for fusion; we need large-scale central generation of electricity to meet base load power requirements for large cities like London, New York, Delhi, Rome.
2.21	Big city HK shots, chemical plant, NY skyline, pylon, , time-lapse clouds, NY street	Commentary Three out of the six billion people in the world live in cities hungry for power. Industry too runs on electricity. Nearly all this power comes from burning oil, coal and gas. The pollution from these fires is a big problem. But human greed for electricity is unstoppable.

2.49	POV driving, INT cab	John Chesshire Well just looking around us, we've got a lot of shop windows here, which are particularly thirsty users of power. / A lot of restaurants where they've got coffee machines, they're probably cooking by electricity. (Er) There are a lot of offices where they've got printers, photocopiers, (er) PCs at work, and in some of the taller buildings they'll have escalators and lifts. So an enormous range of end use applications.
3.13	NY at night, Times Square	Commentary It seems like it will never end. But it could. We now know that oil and gas are not comfortable, endless sources of power.
3.25	INT cab	John Chesshire If / we look at the North Sea, the UK's main source, that will peak in about 5 years time, and will be very heavily depleted by about 2030
3.37	Power station, turbines, waves	Commentary Power stations use heat to turn water into steam.
3.44		That's what spins turbines to make power. That heat comes mainly from oil, coal or gas.
3.54	Nuclear reactor GVs	Commentary Nuclear power stations use an atomic process called fission. It splits heavy atoms like Uranium to make the heat. It doesn't produce greenhouse gases, but there is a huge drawback.

4.08		John Chesshire The major problem with fission is what to do with the nuclear waste at the end of the reactor's life. And all those governments which deploy such reactors are now facing this big issue. What do we do with long-term disposal on very high, highly radioactive nuclear waste.
4.25	Nuclear reactor/Turbines	Commentary Nuclear plants make lots of power all the time but with a huge toxic legacy. The wind, the waves and the sun's rays make clean energy, but much less of it.. Fusion from the heart of the Sun could give us the best of both worlds. Constant, plentiful power. No long term radioactive waste. No chance of a meltdown.
4.46		Alan Sykes It still remains that fusion is inherently far, far safer and, more environmentally friendly, than fission, but it's just much more difficult to work, to get it to work.
4.55	BCU Sun	Commentary If we could make fusion, in our own Sun, on Earth, we could use its enormous heat directly – instead of oil, gas, coal and nuclear fission.
5.08	B&W stills old fusion research	Commentary Research began in the 1950s. With crude equipment these scientists tried to capture a tiny piece of the sun.
5.18	Reunion – tilt up from newspaper pics	Commentary An early, famous British experiment, a generation ago, was called ZETA
5.24	Reunion	David Goodall OOV (This was in the time of ZETA, 1958…)

5.31	Alan	Alan Sykes I myself heard the stories from ZETA in the late 1950s where they thought it was actually working, unfortunately some way off there. But that, that I thought was a very inspirational thing, and many of us here are very devoted to the concept of fusion.
5.46	Sunset, SOHO BCU sun orange/green	Commentary Satellite images reveal the Sun as a giant ball of hydrogen. It's so hot that hydrogen atoms break down, and turn into a plasma – the fourth state of matter. Under the huge pressure of gravity at the centre, the hydrogen atoms fuse together to make helium. One gas becomes another. The clean, powerful, fusion reaction makes light and heat that we feel on Earth 90 million miles away.
6.19	SOHO/TRACE BCU SUN	Commentary It takes enormous energy to create a fusion plasma on Earth. Even the most powerful research machines can only hold one for a few seconds. Most earthly plasmas last a fraction of a second. Once it's stable, a power station plasma must produce much more energy than it consumes, so there's enough left over to make electricity. That's the key to fusion power.
6.50	Sea – NT skyline	Commentary The fuels for fusion on earth are two special kinds of hydrogen. There's enough dissolved in the oceans for perhaps millions of years. The waste gas is ordinary helium.

7.11	EXT Culham. Title: Culham, UK	Commentary The Culham research facility is where the most powerful plasmas on Earth are imprisoned. But for all their power, fusion plasmas are fragile, and that makes them safe. A fusion machine cannot melt down. If something goes wrong, the reaction just stops.
7.36		Inside it's a giant metal doughnut shape. The Russians who invented it in 1968 named the system a "Tokamak".
7.45	Alan with tube	Alan Sykes The first Tokamaks were shaped a bit like is shown in here. This is actually part, a segment of the torus of Culham's first tokamak. It's circular section, quite small.
7.58	Remote handling in JET, remote handling control room, BCU graphic of JET and arm	Commentary "Torus" is what mathematicians call this special, doughnut-shaped vessel.
8.05		VO Over the years, this shape has evolved, to make more powerful plasmas.
8.17		Commentary Theorists have noticed that compact shapes are generally more efficient.
8.30		Commentary They hold more energy. They produce better fusion.
8.34	Alan by START	Alan Sykes Tokamaks have got larger, they've become more elongated and D shaped in section, and the bit in the middle has got relatively smaller. About 15 years ago, we began to study what was the limit of this process, how compact you can make this equipment.

8.53	JET remote handling	Commentary The traditional Tokamak can only be so small. It wraps its plasma round a circle of vital machinery. Most of this has nowhere else to go. A compact plasma means a completely new design.
9.09	Peng & Strickler paper,	Commentary In 1986 an American scientist, Martin Peng, proposed a revolutionary experiment to create a compact, or spherical, plasma.
9.17	Martin Peng in his office	Martin Peng Plasma shape has a strong effect on plasma stability. How stable you can hold the plasma together without the plasma going caput. One of the primary response to this idea was that it's basically impossible to build.
9.36	Rostrum	Commentary Martin Peng's theory showed the unusual spherical tokamak could be more efficient and more economical than regular machines. It might be a better way to trap a hot plasma on earth. But it remained just a theory.
9.54	USA roadside, houses, subway, bridge view	Commentary Despite its huge need for energy, the USA decided not to pay for Martin's experiment. He became a globetrotting scientific evangelist for the idea of a compact plasma
10.06		Martin Peng I began to / give talks about this idea. And how it maybe very interesting to study it and I visited Culham a couple of times, since then, and I think I got Alan Sykes very interested in looking at this.

10.22		Alan Sykes I was the person jumping up and down saying, why doesn't somebody build one of these things, because theoretically there looked to be a lot of advantages.
10.30	Alan by START	Alan Sykes There are two ways of doing that . Either you have a major project and lots of review committees and five years down the line, you may or you may not get your money. Or, if you have enough bits and pieces and just a bit of, sort of petty cash, you can try throwing just a test of the concept together.
10.46	Zoom in to Alan from defocus wine glasses	Commentary That test of the concept is what the reunion is all about.
10.52		Tom Todd Alan was charged to create a presentation to
		Alan Sykes I volunteered to be chairman of that group Tom Todd Ah ha you volunteered, very commendable. And er Alan Sykes Well it was either that or doing, getting involved with something I wasn't interested in

11.07	Tom Todd, cutaways other team members	Tom Todd Right, right. Good piece of volunteering. And the Spherical Tokamak won the review hands down. And so our the division head at the time, now the Director, Derek Robinson, said to his department managers, about five or six of us, "right you lot I want you to give me a cheap way of building a Spherical Tokamak, since it's won this review" /
11.27		Derek Robinson Some people had done some theory in the states, some people at Culham had done some theory, it might work. And everybody said, well we don't know how to do it, though, it's all very well saying, let's have a nice spherical system. How would you create one in the first place, how would you make it, it's all very well saying you could do it, but how would you make it.
11.42		Tom Todd And the only person that came back in the next few days and said "this is how we might do it, sir" was me. And I sketched it on a whiteboard and he said "mmm you've got the poloidal field coil layout wrong there because flux conservation means lblblblblblbl". So he said "do it like so and so". So I played around a little and said "oh you mean a bit like this?" And he said "yes that would now work".

12.03		Derek Robinson But then the big problem, as usual was, were are you going to get any money from? And then we realised that we had a real problem, because Government said, ‘No way, no way, this is mad idea, mad idea’. Our European colleagues said, ‘Go away, (er) we’re not going to provide you with something with a mad idea like this, it won’t work’.
12.17	Alan by START	Alan Sykes The idea of having a, a plasma a, a metre across in the middle of a large tank, they thought the plasma wouldn’t stay there it would be unstable. Because conventionally you have a fairly close-fitting shell which surrounds the plasma. And we weren't doing that.
12.31	SOHO solar disc	Commentary The sun keeps its plasma under control with its enormous gravity. No gravity – no fusion.
12.44	Graphics – atoms	Commentary The core of the sun is at fifteen million degrees. The hydrogen atoms break down into a mixture of electrons and nuclei. – a plasma. The nuclei repel each other, but the pressure forces them together. They fuse to form helium. And this releases energy.
13.15	TRACE images	Commentary The plasma conducts electricity, so it moves to magnetism, into patterns on the surface of the sun. The Culham team wanted a machine to discover how to control plasma on earth.

13.29	START details	Commentary It's a trick which needs lots of electricity, and huge magnets. With no direct government money, the team needed an ingenious way to put the machine together
13.38		Derek Robinson I'd visited Alan Sykes at home several times, and on one occasion I remember going upstairs and discovering that the whole bedroom was full of car bits, in other words, he put cars together, and motor bikes actually as well, from bits and pieces, and realised that one of our key modellers, more theoreticians actually had a practical bent, and could put things together, and I thought, 'That's just what we want'
13.57		Alan Sykes People thought that the techniques that I used for that, scrounging from scrap yards, and things, would come in very useful
14.04	START stills	Commentary Construction began in 1989, 50 miles west of London, with no official government funding
14.11		Alan Sykes I don't think we got anything literally from a scrap yard, it was the care and custody store it was called, where (er) people's favourite bits of kit from past experiments were stored away, and so we raided that. It was a sort of scrap yard of Culham.
14.27	Tom Todd still & rostrum move to emphasise him	Commentary The team also needed Tom Todd's input to help them build the machine.. But his expertise was in demand elsewhere.

14.36		Alan Sykes During the daytime he was very busy with meetings / but at lunch times, we realised that he would have an hour off for refreshment and recreation. So we started meeting at lunch times in the Machine Man Pub, where we would have a drink and a lettuce leaf or two, and he would look at the drawings we had made up and advise us on how to get the machine / built.
15.00		Tom Todd We would go to the Machine Man, spread the blueprints out amongst the beer and the ham and veal pies or whatever, and using the beer bottles to hold the corners of the blueprint down, we'd argue about sections of copper and vacuum pump speeds
15.15		Derek Robinson We weren't supposed to be using Government money at this stage for building this device, / and of course it's sort of nice relaxed atmosphere, and that's Alan likes to do things, it's not so rigid and formal like what we might have with our project planning meetings actually here.
15.30	Pub sign, START machine rostrum	VO In 1991, after many working lunches, the machine was finished. It was called "START", short for Small, Tight Aspect Ratio Tokamak.
15.40	Construction rostrum	Commentary It's a remarkable collection of spare parts.

15.44	START tilt down	Alan Sykes The vacuum tank for example was used in a (er) experiment in the 1970's \ it had been lying unused on the runway outside the lab, since then. It's an aluminium tank in sections, so the vacuum conditions aren't particularly good for plasmas. (Er) But still we got very good results with it.
16.01	START details	Music
16.05		Alan Sykes It looks a bit (er) Heath Robinson construction, these wires over here look rather tatty, and you can see signs of leak seal being put on there, because we, we, when we had a leak we just put some spray leak seal on.
16.23	START details	Commentary No-one knew for certain it would work. Fusion research has had its share of failures.
16.39	START plasma B&W movie	Commentary But it worked spectacularly well.
16.44		Commentary A high speed camera revealed a delicate cloud of hydrogen plasma at 5 million degrees. It lasted just long enough to take measurements.
17.02	START pink	Martin Peng Oh, that was exciting, that was really very, very (um) exciting to me and of course a little bit of envy in there, that we couldn't do it in the United States. / the first plasma suggested that the basic idea / is basically sound, it can contain high temperature plasmas.

17.25	START control room archive	Commentary Once the machine was shown to work, official government funding became available, and the team began detailed research
17.33		Brian Ward Well the physicists would say what they'd want, and it was my job to give them what they wanted. And the physicists would come and say "the bloody thing's broken down" and I would have to go in and fix it.
17.42		David Goodall I was dragged in very informally. I wasn't allocated a particular job. And Alan was very very good at capturing people and getting them to bring equipment along so he didn't have to spend any money.
17.55	Archive – Alan in the basement	Commentary The team found some unusual ways to stretch the budget.

18.03	In pub	Alan Sykes This is the world's first spherical tokamak, a picture of the plasma in there. / This is actually a / picture taken with a sort of glorified, ordinary camera, with a mechanical shutter. So there's a bit of a delay on the shutter even though you trigger it precisely electronically. There's a few tens of milliseconds delay. And so we made many blank films, because the plasma discharge only lasted about a twentieth of a second. But if you take them to Boots, on the sort of one hour service, they don't – they didn't use to charge you for blank films. So Marcus used to go on his motorbike to Boots of Didcot at lunchtimes. Sometimes he'd come back with some pictures, and sometimes he'd come back with a blank film
18.45	Peng rostrum	Commentary Even Martin Peng came over from the states to lend a hand.
18.48		Martin Peng Well once the experiment is getting going (um) its impossible to stop me from visiting Culham every chance I got.
18.58	START plasmas	Commentary Martin was keen to increase the power of the machine. One way to do that was to heat up the plasma with a special particle beam. There was a spare system in the States.

19.10		Martin Peng Derek and I was just chatting, during the meeting. I said “Jeez, wouldn’t it be nice if we actually bring over a neutral beam system to put on START that will give it some additional heating.” And that’s how it happened
19.22		Alan Sykes It’s about the same size tank as, as START is itself. But this injects high energy (er) hydrogen into the plasma, and this heats the plasma inside the tank. And by doing this we are able to get a world record value of, a sort of an efficiency parameter. Which is the amount of plasma you can hold for a given magnetic field. And we got three times higher than any other tokamak got in the world. And people were really amazed at this.
19.56		Commentary Before the Spherical Tokamak, this kind of hot, high pressure plasma had only ever existed in stars.
20.05	START plasma	Derek Robinson So here on earth we could do something which had never really been done before, and we could keep it there, we could keep it hot, and sustain it, and that to me was great, and that was even better than any of our theoretical modelling would have suggested, that was great achievement.
20.21	START archive, screens, alan at desk into slomo	Commentary The experiment produced a huge quantity of data. Some of it is still being analysed. But eventually the first spherical tokamak was retired from service.

20.37	START wake, taking photos	Alan Sykes (so anyone else who's actually worked directly on START, interpreting it, or fixing it and all the rest of it…)
20.43	Photo taking etc	Alan Sykes No-one thought that START would have lasted six months to a year. / people would have thought it would just have demonstrated the concept worked, and then you would have gone on and built a more substantial experiment. But the concept worked so well, that START actually lasted for about 8 years
21.01	Photo taking	Commentary By the end of its life, START had proved that the Spherical Tokamak was not the mad idea most people thought. It broke records for the efficiency of its plasma. It showed a cheaper way to make a Sun on Earth. And similar machines might one day power the world for their children.
21.24	Machine Man exterior, interior with eating etc,	Commentary When the machine was switched off for the last time the team held a wake. In the Machine Man, naturally.
21.36		Alan Sykes Well there's a sense of nostalgia, but I, I still see the people, and they don't look to be getting much older, because I'm getting older myself. (Um), but it's nice to see the machine's still there. But of course, we've got the new one now, and that's exciting, so the, the physics work is, is even more exciting now.

21.52	Archive – MAST delivery	Commentary Delivery day for the new machine. A purpose built ten million pound big brother. At least twice as big in every dimension. The next step towards a spherical tokamak power plant.
22.07	MAST machine room	Commentary It's called the Mega Amp Spherical Tokamak, or MAST for short.
22.18		Commentary It's a bigger machine, and a bigger project.
22.23		Alan Sykes It’s still good fun progressing along the way, and finding out new things, and (er) trying new techniques, and know that you may be making a significant forward along, along the road.
22.33	MAST control room, pellet room, shot fired	Commentary Today's fusion research is aimed at building a power station. One problem they'll need to crack is how to get fuel into a cloud of gas at the same temperature as the centre of the sun.
22.51		Commentary One promising method is to shoot frozen fuel pellets right into the plasma.
23.01		Today the MAST team are trying out their pellet gun.
23.11		Timing is critical. The pellets travel 25 metres, and they must hit the plasma pulse at just the right instant.
23.20		(Pulse imminent)
23.24		(Five seconds)
23.33	Firing sequence	(… and that's it, and that's the the pellet gone)
23.40	MAST plasma	Commentary The high speed video camera records the result.

23.45		Commentary The plasma forms around the central column, locked in place by powerful magnets.
23.52		Commentary A trickle of fuel makes a bright dot at the centre.
23.58		Commentary Then from the left, a few tiny pulses as the pellets hit.
24.06	Close up pellets hitting	Commentary Pellets made from a simple gas, which comes from ordinary seawater. One day this technique could deliver fuel to a fusion power plant.
24.19	Alan Sykes on phone, Martin Peng on phone	(Hello Martin, how are you…)
24.21	NSTX area, Martin and Masa walk in	Commentary With START a success, Martin Peng at last received the go-ahead for a US machine: the National Spherical Tokamak Experiment. A fusion plasma cannot make a weapon, so governments are free to co-operate.
24.36		Martin Peng We work diligently to try to reach a flagpole as soon as we can and (er) we have common and different flagpoles in our research programme
24.50	Alan phone Martin	Alan Sykes It's a friendly competition, and, and we compete at conferences. We, we often each have an invited paper, and we try and present better results than the NSTX lot have got.

25.01	NSTX shots	Martin Peng It makes the cooperation very exciting and also at the same time, I, shall we say, gives us strong incentive to really work hard
25.10	NSTX exteriors, NSTX interiors, Brooklyn Bridge	Commentary The spherical tokamak could make for smaller, cheaper power plants, because it's very efficient. A smaller plant is easier and cheaper to build, and to dismantle. Waste fuel from today's nuclear plants is deadly for thousands of years. There is no such waste from fusion fuel. Although the metal structure of a fusion plant does become radioactive, it won't be a burden for future generations.
25.38		Derek Robinson You choose materials so that they decay quite quickly, typically over the life of a fusion plant, 20/30 years. So you can recycle them, you can use them again, and use them in the plant
25.54	Alan/Derek chatting	Alan Sykes (… h-modes have been different. They've been a lot better in may ways …)
25.58	Derek/Alan chat	VO Scientists no longer discuss "if" a fusion plant can be built. The question now is "when?" It could be fifty years, but it could be twenty. Derek Robinson (… coming back to the central question: how are you going to get the LI down…)
26.11		Commentary And there are more and more evangelists for what they call "fast track fusion"

26.15		Derek Robinson Why don't we speed it up, do things in parallel. Focus much of the international effort, don't all repeat what you are all doing everywhere across the world. Focus on key elements, split the key tasks up among the nations and bring it together on a much shorter timescale.
26.32	MAST plasma – colour, no pellets	Commentary The smaller, cheaper spherical tokamak might help us avoid the energy crisis which deep down, we know is coming.
26.47		John Chesshire Well I have a daughter who is 16 years of age, and I often reflect on what the future might bring for her, as we use up all these cheap fossil fuels, if we are adding to carbon in the environment. / We have to begin to diversify, to renewables and to fusion, in my view.
27.06		Martin Peng I It is a non-polluting energy source and the fuel for such an energy is available to everyone and it's not limited to some deposits or some location. It is everywhere in the sea water.
27.24		Alan Sykes There's still a lot to go, of course, because it's, we haven't got there yet, we want to see what the, what the future of the spherical tokamak is (er) and what chance it has of leading to an economical fusion power plant.

27.39	START control room pan sequence	Commentary The control room is now quiet and used for storage. But the START project was one more step towards the fulfilment of a 50 year old promise. To make electricity, and power the world, from a piece of the sun, trapped in a magnetic bottle.
27.59	CREDITS over sun/insulator shot then iris pull to white out	MUSIC
28.15	END SLATE	

End Credits

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