Presented to the SPIE Symposium on Electronic Imaging,
Santa Clara, CA., February 1990.

3-D TV System for Remote Handling: Development and Evaluation

A A Dumbreck, E Abel and S Murphy

**Harwell Laboratory,
UKAEA, Oxfordshire, OX11 0RA, UK**

ABSTRACT

The paper describes the development and evaluation of 3-D Television Systems. 3-D TV had been developed with a view to proving whether it can be a useful remote handling tool which is easy to use and comfortable to view. The paper summarizes the principles of operation, the initial development, the evaluation trials at UK facilities and it reviews the developments which have been found to give improved performance in terms of speed and accuracy of operations and to reduce the number of camera views required.

1. INTRODUCTION

The Engineering Sciences Division of Harwell Laboratory carries out research and development of remote television systems for remote handling in nuclear environments. The work includes equipment development and human factors experimentation; its ultimate aim is to facilitate the widespread introduction of television (TV) viewing equipment into nuclear plant.

The work includes the development of stereoscopic or three-dimensional (3-D) TV. This programme of work is nearing completion, it has been split up into the following stages:

a - Determine criteria for design of 3-D TV to be comfortable to view and useful for remote operations

b - Build engineering prototype systems

c - Evaluation of prorotypes in various cold mock-up facilities

d - Build 2nd generation system, and evaluate

e - Build 3rd generation, radiation-tolerant black-and-white system

f - deploy camera in radioactive environments

The programme is complete up to stage (e); the third generation, radiation-tolerant camera is built, and trials have begun. The purpose of this paper is to summarize this development and evaluation programme. The work has made available 3-D TV systems which give useful improvements in depth perception for a wide range of viewing requirements and environmental conditions. The systems have proved comfortable to view, easy to use, and robust in operation.

2. 3-D TV

The purpose of the 3-D systems developed at Harwell is to give operators improved depth information about a remote scene. The 3-D systems do this by providing the viewer with binocular information which allows him to perceive a solid image from two flat pictures. The two pictures come from two cameras which are offset a small distance horizontally and whose focussing targets are in the same plane. (The focussing target is equivalent to the film in a camera). The two pictures are identical except for small horizontal differences in image position. These disparities vary with the distance of the objects from the camera, so there are a range of disparities for different objects in a normal scene; they allow the viewer to see the picture in 3-D.

Figure 1 shows a viewer looking at a 3-D screen which allows him to see only the right image with his right eye and the left image with the left eye. Because there is a horizontal disparity between the left and right images of the same object, the viewer is tricked into perceiving the object behind the screen. A 3-D picture is built up of a large number of such points, with different horizontal disparities and therefore different distances behind or in front of the screen.

Some object points may give no horizontal disparity and so their images appear in the screen plane. They have no disparity difference because the object is in the plane in front of the 3-D camera in which the two camera axes cross. The control of the camera axes can thus be used to control the position of the 3-D image relative to the screen. The objects of interest are normally placed close to the screen plane, ie the cameras are converged on the objects of interest. This is important because we have found that viewers can only cope with a limited range of horizontal disparities. The limitation is because the viewer's eyes stay focussed on the screen but they change convergence around the scene to converge at distances appropriate to the image point placement. In other words, we find that the viewer can accept small discrepancies between accommodation and convergence, but not large ones. We have therefore designed systems to enable the operator to keep the image acceptably close to the screen, in a truncated pyramid, as shown in Figure 2.

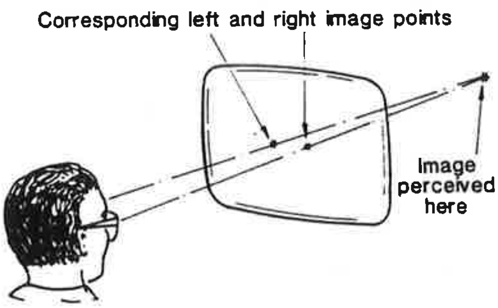

Figure 1, 3-D image Formation

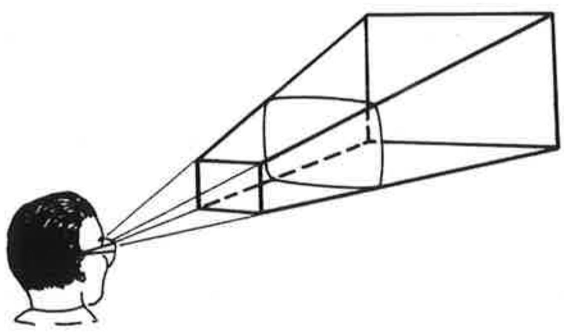

Figure 2, The Truncated Pyramid Encompassing the 3-D Image

3. 3-D TV PICTURES: CALCULATIONS OF SIZE AND SHAPE

The shape and size of a stereo image can be calculated geometrically, some of the more basic formulae are derived below. The pioneering analysis of 3-D images was carried out in the 1950's[1,2] for the motion pictures. The same principles are used in the equations below, though these are expressed in ways more applicable to TV systems. 3-D image shape and size can be defined by the magnifications from object points to image points There are three magnification factors to consider, width magnification (M_w), depth magnification (M_d) and height magnification (M_h). Height and width magnifications will normally be the same, apart from very small discrepancies when the image is viewed obliquely; M_w will be used here to cover both. Depth magnification is subject to different constraints and is, in general, different to M_w. Both M_d and M_w may vary with distance from the camera; in other words, reproduction may not be linear throughout a scene.

Figure 3 shows a representation of a stereo camera and object scene. O represents an object point distance p in front of the 3-D camera, the cameras are converged by axial offset (distance h) of each lens. Expressions for l and r (see Figure 3) may be found by similar triangles, and the camera parallax z, by subtracting l - r

$$z = 2h - \frac{ft}{p} \qquad (1)$$

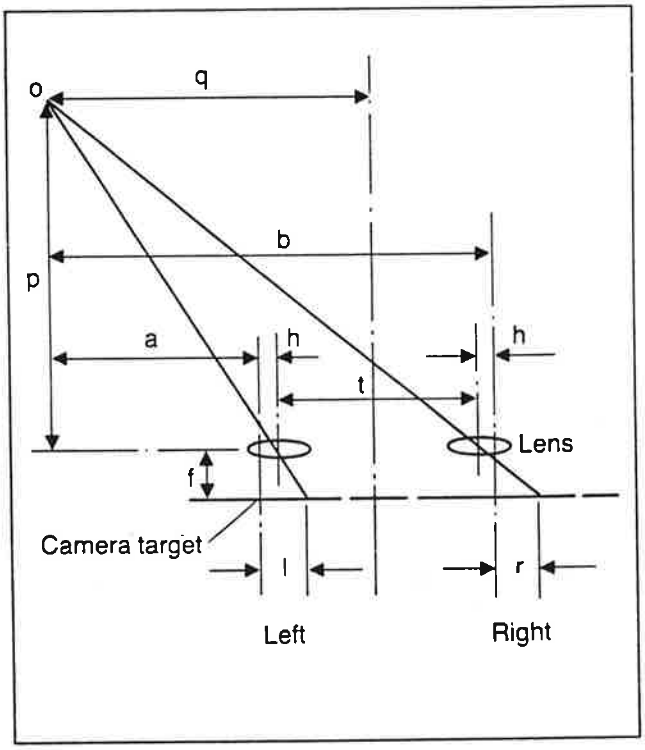

Figure 3, Stereo Camera and Scene

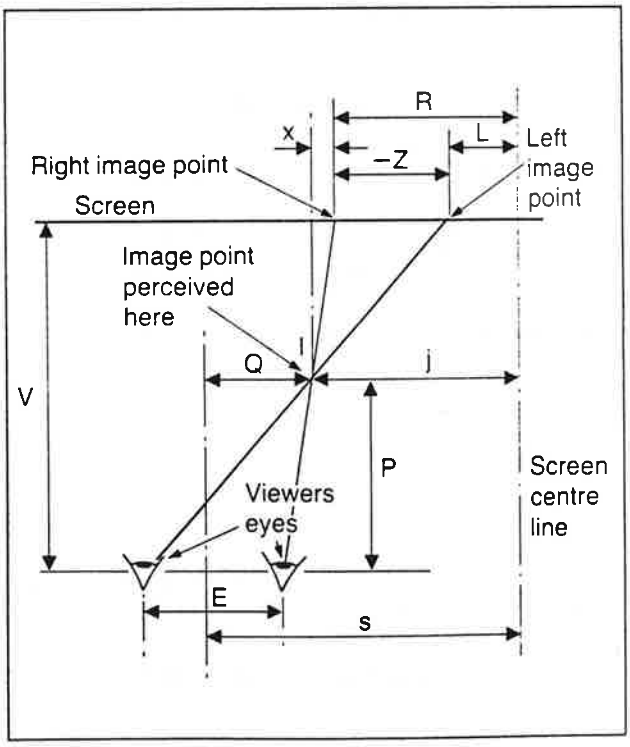

Figure 4, Viewing Arrangement

This parallax is transferred to the viewing screen but it is increased by the magnification factor, M

$$M = \frac{\text{screen width}}{\text{target width}}$$

$$\text{Screen Parallax } (Z) = Mz \qquad (2)$$

The viewing arrangement is shown in Figure 4. In the case of Figure 4, Z is negative because the right image point appears to the left of the left image point. The viewer to image point distance (P) is:

$$P = \frac{V\,E}{E - Z} \qquad (3)$$

$$P = \frac{V\,E\,p}{Mft - p(2Mh - E)} \qquad (4)$$

It can be seen that the equations apply equally well if Z is positive, but that in this case the image point appears behind the screen.

The depth magnification can now be determined by differentiating equation 4 with respect to p:

$$M_d = \frac{dP}{dp} = \frac{VEMft}{(Mft - p(2Mh - E))^2} \qquad (5)$$

Similarly expressions may be derived for lateral position mapping (Q as a function of q, see Figures 3 and 4)

$$Q = \frac{E(Sp + Mqf)}{Mft - p(2Mh - E)} \qquad (6)$$

and differentiating with respect to q gives width magnification:

$$M_w = \frac{dQ}{dp} = \frac{MfE}{Mft - p(2Mh - E)} \qquad (7)$$

The image shape ratio gives the shape of the image at a given point:

$$\text{Shape ratio } (u) = \frac{M_d}{M_w} = \frac{Vt}{Mft - p(2Mh - E)} \qquad (8)$$

Finally we need to know the relationship between the lens offset (h) and the convergence distance. It can be seen by reference to Figure 3 that:

$$\text{Convergence distance} = \frac{ft}{2h}$$

It must be noted that the brain's interpretation of the twin-channel visual information supplied by the eyes is not solely based on the above geometric principles, but is also influenced by other factors and in particular by prior knowledge of the shape of familiar objects. When we are dealing with abstract images, the mathematical basis is closely followed; when dealing with known subjects and particularly images of human figures, the brain tends to modify impressions in order to make the images fit in with prior concepts. In practice we have found that for shape ratios not exceeding 2, the viewer can normally accept that the image is a good representation of the original. We have suggested guidelines for the matching of the left and right pictures, and for the control of depth and shape reproduction.[3,4] We have found that, if these are adhered to, 3-D pictures can be comfortably used over long periods of time.

4. FIRST PROTOTYPE SYSTEM AND EVALUATIONS

4.1 Prototype Camera:

The first engineered systems to be made to the suggested guidlines have been evaluated in non-radioactive conditions in facilities within the UKAEA and CEGB. The camera uses four solid-state cameras arranged in 2 pairs, to give wide and narrow angle stereo pictures. The focus and convergence of the cameras are linked so that both pairs are focussed and converged on the same plane, a single front panel switch movement operates focus and convergence for both cameras. This makes control of the camera relatively simple.

4.2 Prototype Display:

Consideration was given to all of the known methods of display for stereoscopic images. Many of these were set up experimentally in our laboratory in order to ensure that the best method achievable was used. The display eventually chosen uses two monitors set at right angles and viewed through a semi-reflective mirror. Polarizing filters at the monitor faces and in spectacles worn by the viewer separate the left and right images. The spectacles are lightweight and are similar in appearance to sunglasses or corrective spectacles. The display was designed to meet the rigorous picture matching requirements referred to above. This was achieved by careful and rugged mechanical design, and by selection of high quality monitors which allowed the necessary degree of picture adjustment.

4.3 Evaluations:

Preliminary evaluations at Windscale Laboratory showed a 23% improvement in the time taken to complete a typical decommissioning task - cropping a reinforcement bar - via a remotely-operated industrial robot in a mock-up facility. The facility is designed to test and develop equipment for nuclear decommissioning, particularly with respect to the decommissioning of the pressure vessel of Windscale's Advanced Gas-cooled Reactor (WAGR). These evaluations have been reported fully previously[5]. In addition to the time reduction recorded, the study showed a number of other results. Examination of video tapes made of the operations showed that the reduction in time for stereo was linked to fewer discrete movements of the robot. This suggests that operators had better control of the remote operation and might make fewer errors as a result. A number of operators who used the equipment during these trials and other operations expressed a preference to work with the 3-D system.

In addition to formal evaluations, one of the two prototype systems has been used for an extended time in a remote operations facility at the CEGB's Marchwood Laboratory. This has provided an opportunity to check the stability and performance of the camera and display in the hands of operators with no expert knowledge of television equipment. Regular inspection has shown no routine requirements to set up the camera mechanism. Minor drift in monitor geometric alignment noticed after one years use was small enough not to give operational problems and was easily corrected. The display contrast and brightness controls which need to be carefully matched on the two monitors had been locked off during installation so had not been adjusted by operators. The settings had not drifted significantly during the 18 months of use. Part of the design philosophy had been that the operator should not be able to change settings that are not essential for operations. This has been largely confirmed by trials, operators have not expressed a wish for more adjustments, and the equipment has stayed well set up.

5. CAMERA DEVELOPMENT

A requirement to develop a fully engineered colour camera, subsequent to the production of the first black-and-white cameras, has provided the opportunity to incorporate some of the refinements to the original designs suggested by the mock-up evaluations and operational experience. The cameras have been built and were used for the second series of trials at Windscale Laboratory. The camera has included: the choice of automatic or manual iris controls; a mechanism accurately linking focus and convergence, convergence is achieved by axial offset of the lens so no trapezium errors are suffered; mechanically linked iris control giving very accurate iris matching; the position feedback of the focus mechanism which has been used to provide a binocular range-finding facility. The camera uses two re-packaged single-sensor solid-state cameras and a range of photographic lenses which make angles-of-view from 30° to 8° available. As with the earlier cameras, video is transmitted via twisted pairs. The camera is designed to allow radiation-tolerant sensors to be fitted to give a radiation-tolerant and environmentally sealed version.

6. DISPLAY DEVELOPMENT

The polarized light displays use two modified picture monitors set at right angles and viewed via a beam-splitting mirror. Polarized light filters at the monitor face and in spectacles worn by viewers separate the two pictures. These have proved to give good quality pictures which are comfortable to view and with no operational difficulties. We anticipate that this display will be the preferred option for serious use of 3-D television over the next few years, because of its high standard of performance. Some applications may demand smaller displays for a given size of screen. In this case we now believe that a time-division display of acceptable quality could be made, but at considerable financial cost. The display would be required to show a video at twice the normal rate and suitable framestores would be needed to buffer the video, if conventional cameras where to be used. This would give anomalous picture components for moving objects, but we believe that picture quality could be acceptable for most subjects. The polarity switching should be carried out at the monitor face, with polarizing spectacles being worn by the viewer. Care must be taken in the choice of picture phosphor and polarizing materials to keep cross-talk between the left and right pictures to an acceptable level. Auto-stereoscopic displays are feasible; an autostereoscopic TV display has been demonstrated at Harwell. An image-forming screen transmits the left and right pictures to the eyes without the need for a viewing aid to be worn (though the viewer's head position must be reasonably fixed to obtain the 3-D view).

The colour polarized light display developed at Harwell, see Figure 5, is a development of the original black and white display, but using broadcast quality colour monitors which have preset controls for allowing control of the picture shape. By collaboration with the manufacturer, the important preset controls for each monitor have been brought out to a lockable control panel on the top of the displays; this can be seen in Figure 5. A test pattern generator has been included in the system so that the operator can follow a relatively simple procedure to check, and if necessary, adjust the geometry, colour and grey level of the monitors so they are well set up and matched. A cross-hatch pattern is displayed on both monitors to allow geometry comparison - the scan circuits of the two monitors are adjusted until the two patterns exactly overlay. A stereoscopic version of picture line-up generator (PLUGE) signal is used for grey scale alignment signals are asent to the top half of the right monitor and the bottom half of the left. The grey scales are thus displayed on one monitor each. The display is viewed without spectacles so the two scales can be compared. Further details have been given elsewhere.[5]

We anticipate that some training for operators to carry out the set-up would be required, in addition to concise written instructions. Similar developments have been incorporated into new black and white displays. Broadcast monitors are used and circuitry has been specially developed to enable geometric matching of the two pictures with the aid of the cross-hatch pattern generator. The electronic controls remove the need to make adjustments to the picture tube and its deflection assembly which require more skill.

7. EVALUATION OF 2ND GENERATION, COLOUR SYSTEM

Evaluations of this second generation, colour 3-D system, were carried out at the Windscale facility.[6] A task was based on an operation planned as part of decommissioning WAGR; two heavy steel plates were to be moved between stands and a 'toast rack' using an overhead gantry crane. The task involved rotation and accurate positioning of the plates. One was a curved piece of thermal shielding 5cm thick, and the other was flat and 8cm thick. Respectively, these were to be inserted into slots 8cm and 8.3cm wide. Two television views were provided - a main view looking along the slots from 1.6m above the toast rack and an oblique supplementary view - based on camera positions possible for the real operation. The supplementary view was always in 2-D but the main view could be either 2-D or 3-D.

Six operators were timed using both 3-D and 2-D. Half used the 3-D first, the others 2-D. In turn, with each viewing system, the operators moved the curved plate from stand to toast rack, the flat plate to the toast rack and then returned both to their stands. The sequence was then repeated. For analysis, the task was split into sub-components. This showed that the part of the task which required the most positional accuracy benefitted most from 3-D TV. This was the part of the task where the plates were aligned with the toast rack; a 17% time improvement was found for 3-D.

A questionnaire was completed by the six timed operators plus two more who had also used both the 2-D and 3-D arrangements. The 3-D was highly rated on picture quality and ease of use. All except one had preferred using 3-D and would have been happy to do so for extended periods. Some operators commented that the 2-D views could have been better placed - plan and elevation views would have been preferred - but with 3-D, the camera positions were satisfactory. This is in accord with earlier findings that the positioning of a single 3-D view is far less critical than the optimal siting of a pair of 2-D views. A fuller report of this trial has been published recently.[5]

8. CONCLUSIONS FROM EVALUATIONS AND OPERATING EXPERIENCE

The experience of trials and operations shows that 3-D TV systems give a number of benefits for remote handling:

- A reduction in the number of views (cameras) required
- Faster operational times, with greater improvements for elements requiring alignment
- Fewer manipulator movements for a given task, suggesting that fewer errors and collisions would be made
- Positioning of cameras is less critical with 3-D
- Operator preference for 3-D (no ill effects)

Furthermore we can hypothesize that operators are better able to interpret unfamiliar scenes with 3-D TV. From observations made during evaluations, we have made a number of refinements to the designs of the systems which have been incorporated into the second and third generation systems.

9. DEVELOPMENT OF A 3RD GENERATION, IN-REACTOR AND IN-CELL CAMERA

The ultimate aim of the development work on 3-D TV systems is to provide systems which can be used for a variety of nuclear applications including, inspection of gas-cooled reactors; post-irradiation examination and fuel-reprocessing facilities; and decommissioning. The specification for a camera to work in these environments was produced by consulting with experts on remote viewing systems within the UK nuclear industry. The specification encompassed the temperature requirement to 150°C with chilled air cooling, lighting requirements, materials and mechanical constraints. The camera has angles-of-view of 40° and 10° and converges and focusses down to 300mm for the wide angle-of-view. Cable lengths of up to 100m are allowed for. The target radiation-tolerance is 10^6Gy with dose rates to 10^4Gy/hour. This figure requires future confirmation by experiment. We did consider and experiment with the use of zoom lenses for this camera. We believe that it is possible to use zoom lenses in fully engineered and remotely controlled 3-D cameras. However we found that we could not obtain a suitable radiation-tolerant zoom lens because of the limited range commercially available.

The camera manufacture was completed during 1989 and is currently undergoing trials prior to use in an active facility. The size requirement for the camera combined with the use of two sets of fixed focal length lenses for two angles-of-view has meant that the mechanical linking of convergence and focus used in the earlier cameras was not appropriate and that full computer control of the system was required. Computer control is needed because the axial offset required for convergence, and the displacement of the lens relative to the pick-up for focus are different for the two focal lengths. The combined focus and convergence control, designed for simple operation, has been retained. However with computer control it is possible to remove this link, which is made in software and is purely for the convenience of the operator. This would allow an experienced operator to move the focus distance away from the plane of convergence as the desirable focus plane may differ from the optimum convergence plane in certain scenes. Computer control allows a number of other advanced features to be incorporated in the camera design such as monitoring of camera temperature, coolant flow, lens status, and automatic readout of convergence distance at the control panel. The camera is shown in Figure 6.

10. VIDEO TAPE RECORDING OF 3-D TV PICTURES

3-D pictures can be recorded in a number of ways. Two tapes can be synchronized on two high quality machines with a suitable edit controller. This method can give very good results, but is expensive and requires that two tapes are kept together. Some degree of skill is needed to record or play back. We have demonstrated a satisfactory technique where left and right fields are recorded alternately to the odd and even fields of the tape. The tape is then played back via two frame stores which repeat fields, for example, the left field is repeated once while the right field is being read from the tape. Developments in video-tape recording of 3-D pictures have been reported elsewhere.[7]

11. CONCLUDING REMARKS

The trials and subsequent developments described here show that 3-D TV can provide a useful tool for the assistance of remote handling operations, provided that the rigorous design requirements are met. Development is already at a stage where 3-D systems can be usefully employed to enable operators to carry out remote operations more quickly and accurately than with conventional television.

12. ACKNOWLEDGEMENTS

The work has been jointly funded by the CEGB and UK Department of Energy. We thank them for their support and permission to publish this paper. We would like to thank Ed Perrott at Windscale Laboratory for arranging evaluations there. Charles Smith of Stereo Image Techniques has made an invaluable contribution to the developments described because of his thorough understanding and practical knowledge of 3-D imaging.

13. REFERENCES

1. R SPOTTISWOODE, N L SPOTTISWOODE, and C W SMITH, "Basic Principles of the Three-dimensional Film", Journal of the Society of Motion Picture and Television Engineers, Vol 59, October 1952.

2. R SPOTTISWOODE and N L SPOTTISWOODE, "The Theory of Stereoscopic Transmission and its Application to the Motion Picture", University of California Press, 1953.

3. A A DUMBRECK, C W SMITH, and S P MURPHY, "The Development and Evaluation of a Stereoscopic Television System for Use in Nuclear Environments," American Nuclear Society, International Topical Meeting on Remote Systems and Robotics in Hostile Environments, Pasco, WA, USA, March/April 1987, Pages 106-113.

4. C W SMITH, and A A DUMBRECK, "3-D TV: The Practical Requirements," Television, Journal of the Royal Television Society, Vol 25, Pages 9-15, January/February 1988.

5. A A DUMBRECK, E ABEL, S P MURPHY, J HOLT, P M SCHEIWILLER, and V M READING, "3-D TV: Evaluations and Lessons Learned," Proc ANS 3rd Topical Meeting on Robotics and Remote Systems, 4.2, Charleston, SC, USA, March 1989.

6. A A DUMBRECK, E ABEL, J HOLT, P M SCHEIWILLER, and V M READING, "A 3-D Television System for Remote Handling," Proc Int Symposium on Teleoperation and Control, Bristol, July 1988, Ergonomics Society, IFS, Pages 197-207.

7. P M SCHEIWILLER, A A DUMBRECK, and A D CHAPMAN, "Video Recording of 3-D Pictures," to be presented to the SPIE/SPSE Symposium on Electronic Imaging, Santa Clara, CA, USA, February 1990.

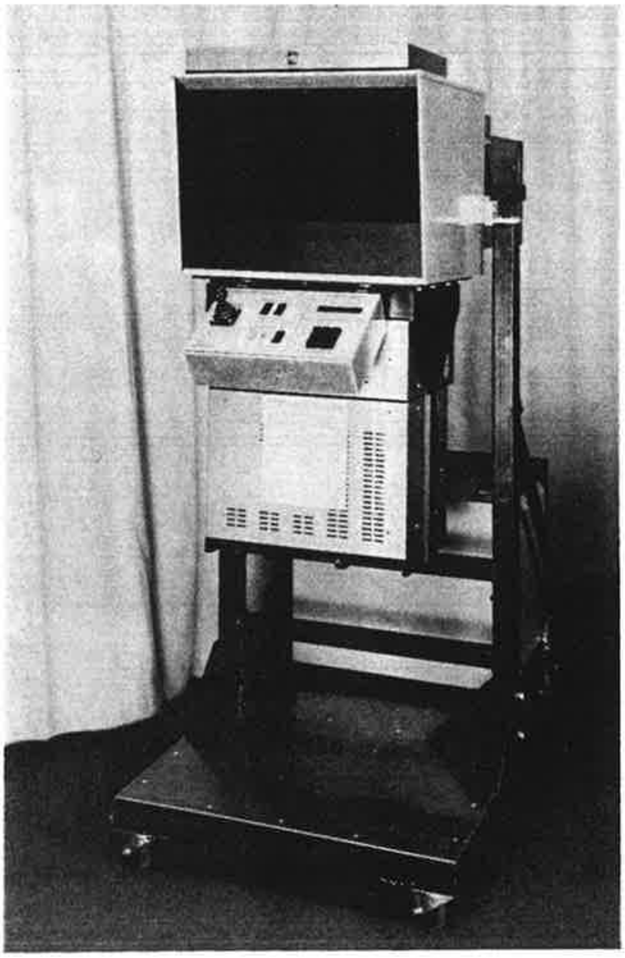

Figure 5, Harwell Colour 3-D Display

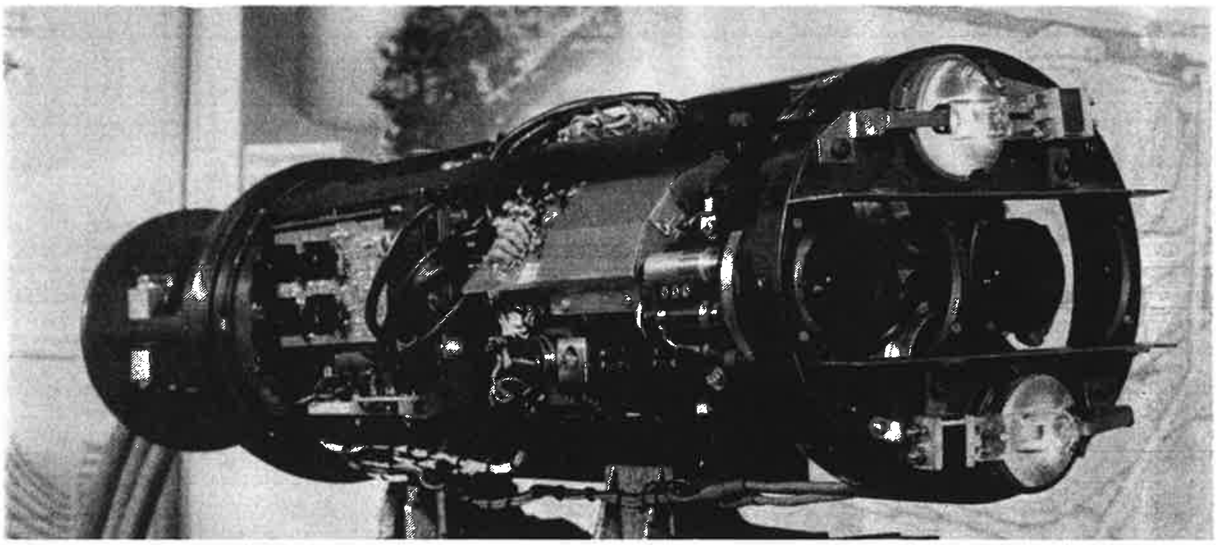

Figure 6, Harwell In-Reactor 3-D Camera
with case removed for clarity