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# IMPROVING THE COOLING CONDITIONS OF THE IRRADIATION GRID OF A 22MW MUTLIPURPOSE RESEARCH REACTOR

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## ABSTRACT

ETRR-2 is a 22 MW Open-Pool Research Reactor designed and constructed by INVAP for the Atomic Energy Authority of Egypt (AEA) at Inshas site (located 35 km away from Cairo city).

The Reactor is aimed to produce radioisotopes for medical and industrial applications, Cobalt-60 and Silicon Doping. It has facilities for neutron activation analysis, neutrongraphy as well as neutron beam and other irradiation facilities useful widely used for basic or applied research.

During the commissioning tests unexpected non-condensable gas bubbles appeared when power was reaching 15MW and over.

As a consequence a careful investigation was undertaken to find out the root causes of the phenomena and it was concluded that bubbles came from certain positions located at the irradiation grid while the fuel elements and the reactor core cooling system (i.e. nuclear safety) were not involved.

The analysis made showed that hot spot appears in structural materials due to the lack of coolant flow resulting in locally favourable conditions for degassing. The problem could not be solved by a simply increase of the available mass flow because of mechanical and geometrical design flaws resulted in uneven flow distribution through the existing channels.

Different proposals were studied and their effectiveness was evaluated using modelling tools and experimental observation (laboratory and on site test).

Finally a set of specially designed mechanical devices placed at the irradiation grid flattened the flow distribution and assured the clearance of the channels. In addition the total mass flow was also increased.

The modifications proved to be successful and the reactor was able to run at its full power without producing bubbles while it maintained its design functionality and capabilities.

This paper gives a brief description of the reactor jointly with the mechanical and flow characteristics of the affected zone. The methodology used, the main conclusions reached for the diagnosis, experiences held in mock-ups and at the reactor test results obtained are also presented.

**Keywords:** Research Reactor, Channel cooling, Irradiation grid, Irradiation facilities, Gamma heating.

## 1 INTRODUCTION

The ETRR-2, designed and built by INVAP at Inshas, Cairo for the Atomic Energy Authority of Egypt, is a 22MW(thermal) multipurpose open pool reactor with several facilities for medical, physical and industrial applications. Among these facilities ETRR-2 is able to produce a wide range of radioisotopes including Co-60 and silicon (by NTD technique) as well as activation analysis application by gamma scanning. Its five beam facilities allow obtaining thermal, epithermal and fast neutron flux for neutrongraphy and other physical research.

The source of neutrons for the facilities is the Reactor Core composed by 19 low enriched uranium fuel elements (FE) located inside the Lower Chimney made of Zy-4. The Reactor Core Cooling System (RCCS) removes the heat produced in the core (95% of reactor power) using downward flow.

Outside the core zone there is a complex assembly of different mechanical elements as neutron reflectors, shielding, guide tubes, nuclear instruments and various irradiation devices see *Figure 1*.

The Irradiation Grid (IG) is a supporting table surrounding the core with a regular mesh of holes to allocate the nozzles of Removable Boxes (RB) of different types; they have the same external dimensions (80x80x800mm) and one of the following:

- Irradiation Box(IBI): Al-1100 made boxes, used normally void designed to hold different irradiation targets
- Beryllium Box (Be): Metal Beryllium made used as neutron reflectors to shape the flux at certain zones
- Aluminium Blocks: Aluminium made compact boxes to suit the neutron flux to the thermal column

Intensive gamma and neutron flux generates heat in all the mass elements placed around the core (5% of the reactor power). As the flux increases as much closer is the distance from the core a dedicated heat removal system exists for cooling the elements at the Irradiation Grid.

The Reactor Pool Cooling System (RPCS) takes water from below the irradiation grid through the cooling holes and makes the flow going between the elements placed above it. In this way the bulk temperature in the pool is kept below 40ºC. while the core coolant temperatures are maintained below 45ºC by the Reactor Core Cooling System (RCCS).

Removable Boxes are arranged on the IG in such a way that there is a 2mm gap between facing walls to allow the water to flow downwards. When a position of the IG is not used, an Irradiation Plug (IP) closes that hole to reduce the by pass flow through the channels.

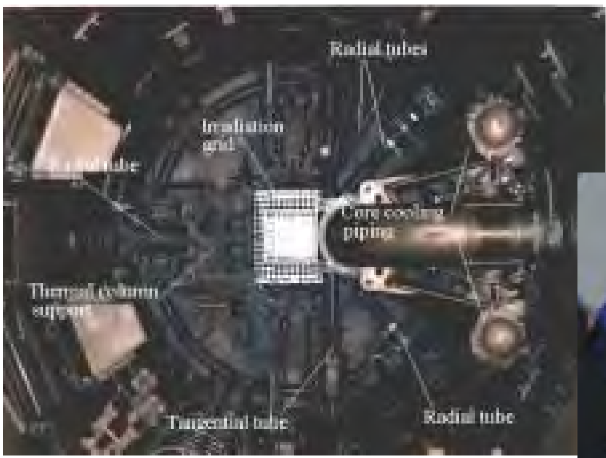
During commissioning incipient bubble occurred when the reactor was operated at 15MWth and over, this effect has not been envisioned during the design stage. The bubbles of a diameter from 1 to 3cm at a rate dependent of the power level, were produced somewhere inside the reactor pool in the neighborhood of the lower chimney. Figure 2, shows the configuration of the IG with the bubbling spots encountered.

The existence of bubbles in Pool Type Reactors (e.g. at MTR or Triga Type) is not a rare issue, since the complex lay out surrounding the core makes it feasible the existence of water stagnation or poorly cooled zones allowing heating build up that rises the temperature locally and generates bubbles by “degassing”.

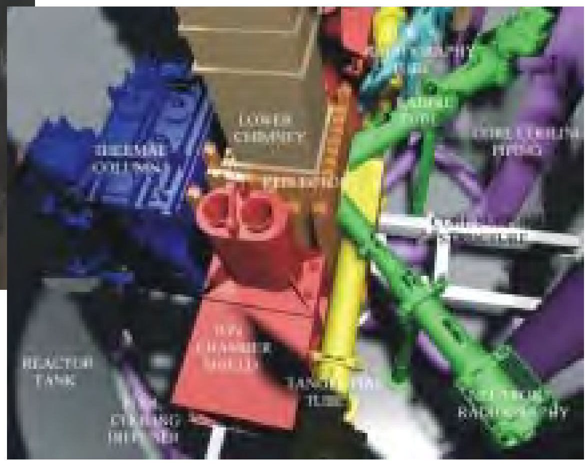
Nevertheless the relative low power level for the bubbling onset and the increasing rate observed at the ETRR-2 brought up some concern on the cooling conditions inside the Reactor Pool. Therefore a special investigation was initiated to find out root causes and evaluating possible solutions to implement.

To minimize the outage of the reactor all the site observations and works should be performed underwater with the full core loaded (highly radioactive), while some zones were not accessible for modifications or changes representing an additional constrain for the work.




*A: Top view*




*B: Simplified 3-D View*

*Figure 1: Reactor core and pool internals*

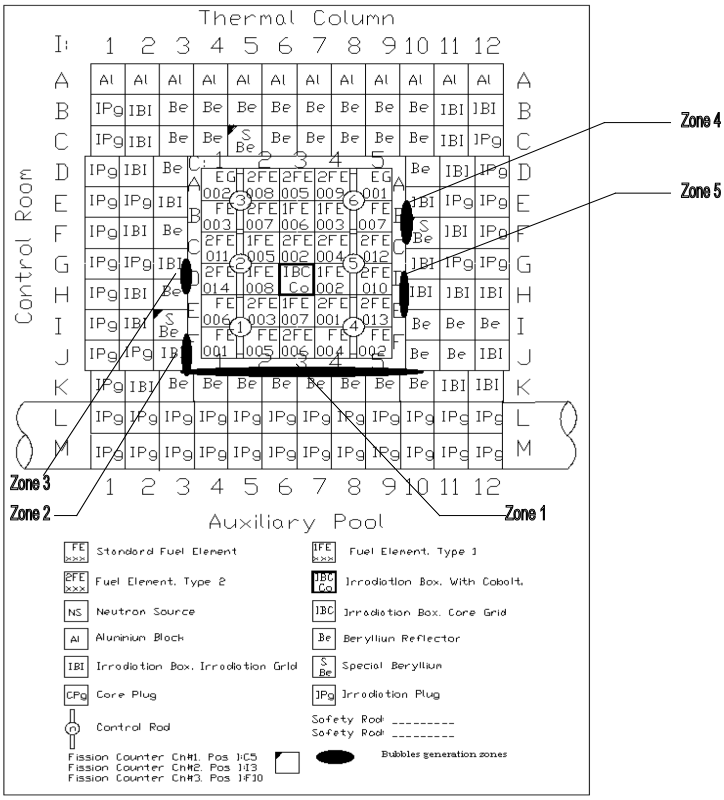



*Figure 2: schematic view of the irradiation grid (bubbles spots indicated as dark zones)*

## 2 ANALYSIS

### Direct observations

Being the core located in the reactor pool and physically connected with the sourrounding water there was some initial concern regarding whether abnormal conditions should exist in that zone.

We made a series of observations with the reactor working at near or above the onset level. This included the use of underwater TV cameras (detached after used in a high radiation field) to record hidden parts close to the Core that could not be reached by direct view from the top of the reactor pool.

Bubbles were harvested when reaching the surface to determine its chemical composition through gaseous chromatography of the samples among other analysis.

The analysis concluded that bubbles were originated in the irradiation grid at certain defined places, closer but still externally to the core zone and not related to the Core Cooling System.

The following findings were obtained:

- Bubbles were not produced inside the reactor core
- Bubbles were generated in some hot spots of the irradiation grid close to the core at specific and repetitive places
- Bubbling was dependent on the cooling flow through the grid and reactor power level
- The diameter and number of bubbles were reduced when flow in the bubbling zone was increased
- Bubbles were composed mainly from non-condensable gases: $N_2$= 62%, $H_2$= 22% and $O_2$= 16%
- The bubble composition measured is in agreement with estimates on the thermodynamic balance of water with air dissolved through balance and hydrogen resulting from water radiolysis
- Qualitative determinations through mass spectrometry to verify the presence of other gases yielded only minor amounts of carbon dioxide, characteristic of the air-water balance.

### Channel Condition Modelling

Energy deposition calculations due to neutrons and gamma rays showed a maximum thermal energy of 15.1 watt/cm$^2$ on the chimney face, 5.7 watt/cm$^2$ on the beryllium and 3.9 w/cm$^3$ on the water gap.

The calculation of flow distribution within the different channels at the irradiation grid was first made using one dimensional analysis but the results were not useful since the channels are not tight enough to be considered one-dimensional since they are formed by adjacent mechanical components that allows lateral current lines across the channels. Therefore a detailed calculation of zones adjacent to the reactor core through 3D finite elements was carried out.

A simple repeated geometry of a long box (beryllium reflector) and two short plugs was modeled, with this calculation. Figure 3 shows the water flow in the mid plane of a gap between the beryllium reflectors, as well as the directions of the water with the velocity vectors and, in color, the magnitudes of such velocity (limited within the 0-1 m/s range).

It can be seen that no water channel exists along the full length (800mm) of the Beryllium reflector wall; only the lower zone (about 100mm near the suction point) was refrigerated while most of the element had no forced cooling, being the velocity at the upper part of the channel null.

The reason was that adjacent element (short plug) shortcut the vertical flow of the Beryllium wall due to the much lower pressure loss of the crossing (horizontal) path.

Numerical estimations showed that even with minimum clearances (less than 1mm) at the back to the first row, allowing cross flow would dramatically reduce the effective flow through the channels (the tightness required for mechanical adjustment was not easy to get due to the nature of the underlying design and accessibility of components).

Heat transfer in natural circulation proves insufficient to prevent high water temperatures necessary to produce bubbles.

A rise in the water flow through the grid does not lead to a proportional increase in the cooling of the channel with the chimney.

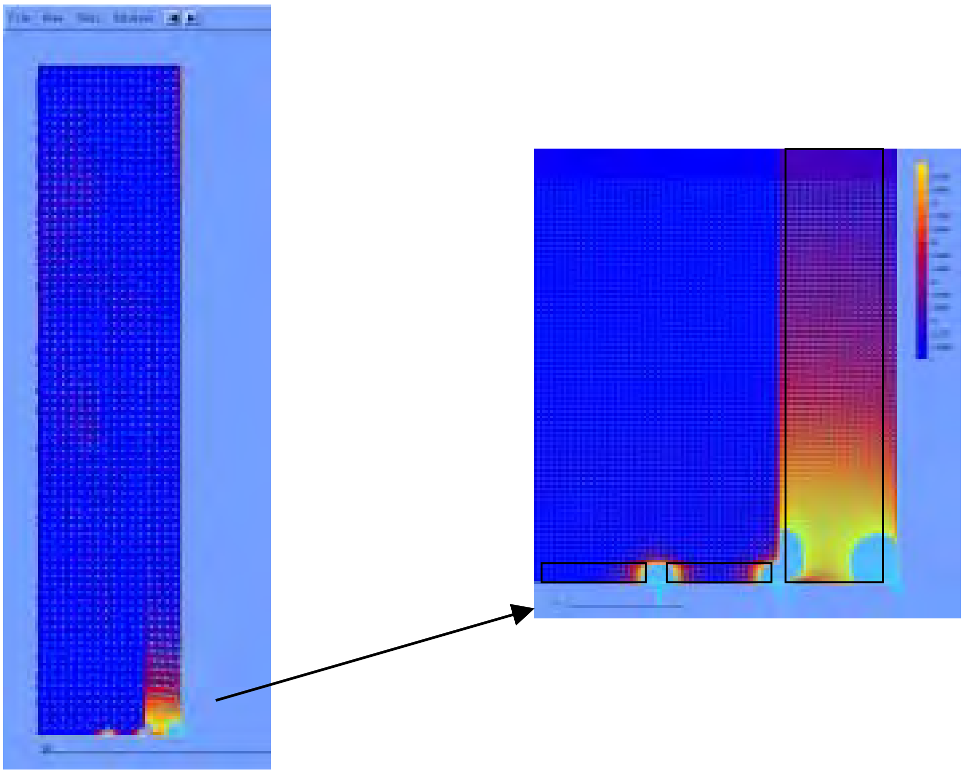


*Figure 3: Water flow in the mid plane between beryllium reflectors facing the Reactor Core*

### Laboratory Tests

A basic system was built to analyze the conditions in which the phenomenon is produced, simulating geometries present in the irradiation grid of the ERRT-2 reactor. Several tests were conducted simulating thermodynamic conditions of the water at the Irradiation Grid (P = 0.2MPa, $T_{sat}$= 120ºC) for the following situations:

- The top chimney frame
- An ideal channel
- A channel with walls in contact
- A channel cooled through natural convection

From these tests we gathered that starting at bulk temperatures between 60-70ºC the bubbles were produced at the metal hot surfaces if the flow velocities were relatively low.

These temperatures were below the theoretical value for thermodynamic equilibrium of the gases found and falls far away from the water saturation temperature at P=0.2MPa.

Therefore we concluded that the first and most important mechanism able to produce bubbles at the Reactor Pool was through "degassing".

Figures 4 and 5 show a simplified diagram of the equipment and a photograph of the bubbles produced on a channeled heating rod cooled through natural convection.

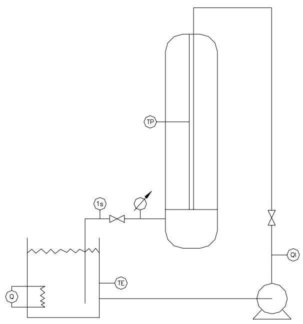


*Figure 4: Equipment diagram*

*Figure 5: Bubbling in a channel*

### Diagnosis

The diagnostics resumed at *"poor or simply lack of cooling conditions in the irradiation grid boxes (mainly near the Berylliums elements) produced high temperature spots that in turn generated air bubbles from degassing of water"*. Nevertheless the cause for that problem relayed on one or both of the following reasons:

1) The channels width (between long boxes itself or with the walls of the lower chimney) were not assured due to the mechanical allowances and adjustment between grid holes and box nozzles

2) There were short boxes adjacent to long boxes that spoiled or shortcut the flow passing inside the channels (formed between long boxes itself or with the walls of the lower chimney)

## 3 FIXING THE PROBLEM

The border conditions to fix the problem were restrictive since the proposed solution should match the following conditions:

- **Nuclear Safety**: e.g. not to downgrade neutron and thermal conditions of the core, reactivity, etc.
- **Mechanical and hydraulic compatibility** with the existing devices and materials at the reactor pool
- **Functionality:** Not reducing the reactor capabilities nor increase the difficulties to normal operating manoeuvres
- **Reversibility:** It should be possible (fair easily) to step back to the initial situation or substitute the new devices at any time during the lifetime of the reactor
- **Durability:** Long term effectiveness of the solution particularly working in a harsh radiation environment
- **Difficult Accessibility:** the irradiation grid is located in a high radiation underwater area only accessed from the top of the reactor pool located about 10 meters above the affected zone (almost one complete side of the irradiation grid is located below the 20 inches primary pipe with no direct view from the top)

The solution came after a series of changes made to the reactor, mainly at the irradiation grid and to the reactor pool cooling system. Each change proposed was first evaluated by using laboratory tests on mocks up representing the interested zone and/or analytical/modelling tools. Special attention was given to prevent (as far as it was possible) the necessity of doing very complex or impossible assembly manoeuvres. Finally the effectiveness it was measured at the reactor step by step by adding one modification at a time until reaching full power without bubbling coming to the irradiation grid. Table 1 resumes the changes done.

*Table 1: Actions taken to improve cooling conditions of the Irradiation Grid*

| # | **Local action desired** | **Overall Effect** | **Solution** Applied |
|---|---|---|---|
| 1 | Avoid or Minimize the By Pass through the *IBI* not in use (empty box) | Increase the effective coolant flow through channels | Use of an internal Plug to the *IBI* when it is not in use (e.g. without the holder for targets) |
| 2 | Avoid cross flow near the Beryllium/Chimney wall channel | Flattening the flow distribution through channels | Replace whenever possible *IP* by (Long) *LPlugs* having the same height the remaining boxes |
| 3 | Avoid cross flow at chimney face near the Tangential Beam (zone unable to place *LPlug*) | Flattening the flow distribution through channels | Installation of a skirt (a framed metal membrane) backing all the Beryllium boxes facing the chimney wall |
| 4 | Assuring a minimum channel width between walls of movable boxes | Flattening the flow distribution through channels | Installation of mechanical spacers for boxes and printed dimples on the wall of some of the Al-made boxes |
| 5 | Increase the overall mass flow of the RPCS | Increase the effective coolant flow through channels | Upgrading the RCPS pumps |

Group #1 and #2 represented a natural extension of the previously designed set of removable elements of the Irradiation Grid. Therefore simple hydraulic verifications and assessment of the reactivity change due to the overall mass added at the neighbourhood of the core was done.

For a typical configuration the modification #1 resulted in 40% increase of the channel flow without affecting the overall mass flow of the RPCS.

The modification #2 and #3 resulted effective in the formation of the channels for cooling.

By upgrading the RPCS´s pumps (modification #5) it was obtained a 20% increase of the total mass flow. This change required minor hydraulic and power supply verification and it was performed only after completing and tested Modifications #1 through #4 to get an extra margin from the conditions necessary for bubble formation.

### Modification #3: Skirt Device

As it could be seen from Figures 1A and 1B (left side), the zone near the tangential beam tube presented some challenges regarding mechanical modifications. Among the most important were the complex lay out and the difficult accessing and viewing from the top of the Reactor Pool due to the location of a RCCS´s pipe.

Replacing of IP for LPlug (#2) was not feasible at the Tangential Beam Tube (a 10 inches pipe along rows L and M of the Irradiation Grid) located at only few centimetres above the grid.

A mock up, 1:1 scale of the grid’s tangential duct area was built to test the different approaches. The model depicted the chimney face, the beryllium block and the tangential tube, the beryllium reflectors, the neutron radiography and radial tube caps and the side shrouds of the irradiation grid. Also a 1:1 scale grid model was used. Figure 6 shows the Mock up view.

To eliminate the cross flow it was decided to install a device (called skirt) back to the line of Beryllium Reflectors. The device comprises an aluminium membrane fixed to a structural frame that closes the irradiation grid jointly with the other existing plates (lateral shrouds). At the bottom, the aluminium membrane was joined to a supplementary grid that tightens the lower zone preventing cross flow near the suction points between the irradiation grid and the Beryllium Reflectors.

Stamped dimples conveniently distributed on the membrane assured mechanically a minimum cooling channel width of 1.6mm. See Figure 7 and 8.

*Figure 6: Tangential Tube zone 1:1 scale mock up*

*Figure 7: Skirt with supplementary grid*

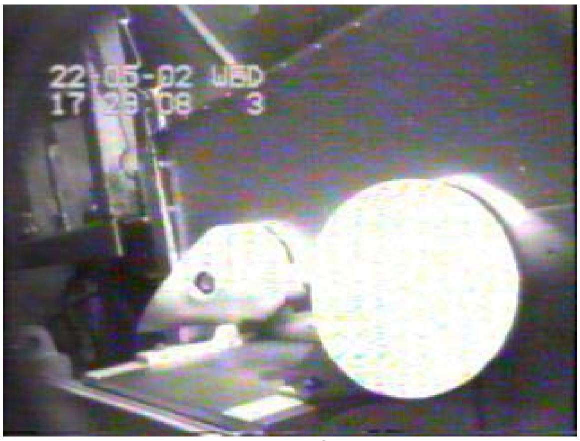



*Figure 8: Picture of Skirt III installed (underwater camera photo)*

The effect of the Al membrane was significant. Cross flow was eliminated and the suction holes produce a net downward flow with liquid velocities near the design values.

Long-term behaviour (possibility of flow-induced vibration) as well as the optimum separation between dimples to avoid it collapsing onto the channel zone were evaluated with Finite Element Modelling by using NASTRAN Code. Stress and strains at the membrane resulting from a maximum pressure difference equals to 5kPa (Maximum pressure difference calculated was 4kPa) gave a maximum strength of 2mm while the calculated water flow dynamics at the top area of the skirt will cause a strain of 10 to 20% of the gap.

Figure 9 shows a graph of the strain of the sheet due to static pressure. In addition it was observed that negative pressure of the channel regarding the static pressure would help in maintaining the membrane towards the Beryllium reflector walls.

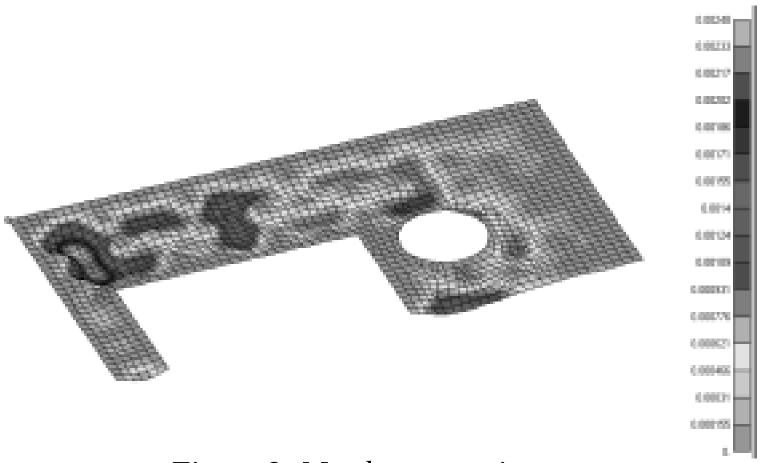


*Figure 9: Membrane strain map*

Prior to the installation at the Reactor Pool a series of design test were conducted in order to set the expected performance of the device.

A leakage test through the metal joint showed that the leakage flow contribution represents some 7% of the minimum flow expected at the channel. Also the maximum strain for stamped dimples was evaluated to prevent possible long-term flaws. The maximum observed strain measured a different operating temperatures (20 to 50 ºC) was less than 1.4mm, showing that no complete blocking of the channel will occur.

For the purposes of detecting possible problems, once the construction of the components involved was completed, assembling manoeuvres were tested and tuned up this included placing the skirt device on the mock up facility on a replica of the Irradiation Grid from an operating station located 10 meters above the grid.

These tests showed the feasibility of the skirt device to be installed as well as the usefulness of the assembly tools.

### Modification #4: Box's spacers

The Position of the IG elements were settled at Grid level (bottom of the boxes) by the Grid Hole and the Box-Nozzle, a pin located near each position of the irradiation grid prevents the rotation of the box when no other element is around. The separation between grid hole centrelines means 2mm channel width. Nevertheless the mechanical allowance of each nozzle-hole pair allowed a lateral displacement at the top of the box elements larger than the channel width. Therefore some of the boxes were virtually in touch (closing the channel) while others had double the mean channel width. In both cases being the removal heat capacity adversely affected.

To tackle this problem it were designed **spacers** that mechanically would maintain the required distance between the outer chimney walls and facing walls of the components installed in the irradiation grid.

### Spacers for Beryllium Boxes

Due to the fact that the end cap of the boxes were different depending of the box type, two different spacers were produced one for the typical Beryllium Reflector box and another for the Beryllium box used for holding neutron fission chamber.

The spacers were carefully designed in machined aluminium to guarantee mechanical resistance and reduce the possibility of being loosed or hook-up between berylliums and other components.

A small prong distributed on its four sides will guarantee a 1.8-mm gap and will act making contact with adjacent components. An adequate frame and device bend the part towards the beryllium reflector handle to prevent loosing. Figure 10 shows photographs of the final spacer,

The spacers for a total of 36 BE were installed 2m underwater at the Auxiliary Pool being the maximum radiation gamma dose rate at the working station 2 mSv/h. An additional benefit was obtained since the use of the spacers facilitated the manoeuvring for assembly the boxes on the IG.

*Figure 10: Beryllium Spacers*

**Spacers for Al Boxes**

For the remaining boxes (i.e. Irradiation Boxes or Long Plugs) being the wall made of Aluminium, 3 mm thick, the most suitable solution was to stamp dimples to assured a mechanical separation not less than 1.6mm in the same way as for the Skirt (see Figure 11).

The dimples were stamped to the existing boxes, already radioactive, by working 2m underwater at the Auxiliary Pool using an ad-hoc hydraulic press device.

*Figure 11:Irradiation Box/Long Plugs with dimples*

## 4 CONCLUSIONS

The bubbles observed during the commissioning tests were completely eliminated for the ETRR-2 working at its design power levels with minimum or null impact on the reactor features and operating capabilities.

An extensive analysis including modelling, experimental and empirical observations at the site allowed setting the causes and the origin of the bubbles.

Among the conclusion are:

- The problem was confined to the Irradiation Grid not affecting the Fuel Elements and the RCCS
- Deficient or uneven flow of the Cooling Channels (due to narrowing, cross flow by short elements and by pass) was identified as the root cause of the problem
- As a consequence of the previous a number of hot spots appeared mainly at the chimney walls (outside the reactor core enclosure).
- The underlying mechanism to produce bubbles was “degassing” the water by temperature
- The solution was obtained by removing short elements and placing new designed devices that equalized the flow while assuring a minimum width of the IG´s channel.
- An additional margin to the bubbling phenomenon was obtained by upgrading the pump capacity of the RPCS.
- The modifications are in full accordance with the basic design and quality criteria of the Irradiation Grid and does not affect the Design Performance and Capabilities of the ETRR-2 facility. Moreover all the elements placed are completely removable for inspection and maintenance.

During August 2003 an ad-hoc expert team of IAEA was commissioned to evaluate different aspects of the ETRR-2. In what refers to the present work the expert team stated that: *“the problem has been satisfactorily solved by the modifications and the process of achieving the solution was acceptable”*.

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