The IRIS reactor design
An International Cooperative Project and the Brazilian participation

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Abstract. IRIS, the International Reactor Innovative and Secure, is an Integrated Primary System Reactor (IPSR) with innovative features that can meet most of the requirements for the next generation of nuclear energy systems. The IRIS project is being conducted as an international development program in a collaborative approach and management openness. This initiative has found a very positive response around the world and the IRIS team grew from the initial four members from two countries to the present number of 22 organizations from nine countries. By the end of 2001, the Brazilian Nuclear Commission, CNEN, signed a collective agreement with Westinghouse Electric Company to officially participate in the development of IRIS. The IPSR concept of IRIS is characterized by the inclusion of the entire primary system within a single pressure vessel, including the steam generators and pressurizer. The CNEN team is responsible for the internal pressurizer design and for the review of RELAP5 input file. The design tasks for the pressurizer have included steam-water volume sizing, pressurizer to vessel physical separation by an internal thermal insulation, surge connections dimensioning and transient analyses. This paper presents a very brief description of IRIS, and a summary of CNEN activities in this project.

1. Introduction

An international collaborative initiative to develop an Integrated Primary System Reactor (IPSR) has created a consortium of industry, laboratory, university and utility establishments, led by Westinghouse to design the so called IRIS - International Reactor Innovative and Secure. Its concept is solidly based on proven LWR technology, but creatively put together with innovative features that can meet most of the requirements considered in the Generation IV Roadmap Study. The IRIS reactor has very good characteristics concerning economics, proliferation resistance, enhanced safety, modular deployment, innovative waste management and fuel utilization. IRIS has been selected as one of the International Near Term Deployable (INTD) reactors, within the Generation IV International Forum (GIF) [1].

The collaborative approach and management openness of this initiative has found a very positive response around the world and the IRIS team grew from the initial four members from two countries to the present number of 22 organizations from nine countries. By the end of 2001, the Brazilian Nuclear Commission, CNEN, signed a collective agreement with Westinghouse Electric Company to officially participate in the development of IRIS.

One of the challenges was the development of the IRIS pressurizer, which is located within the reactor vessel head and has no spray system, thus raising some interesting technical issues. The CNEN team has been assigned the responsibility for the internal pressurizer design and for the independent review of RELAP 5 input file.

The design tasks for this mission include steam-water volume sizing, design of the physical separation between pressurizer and reactor, surge connections dimensioning, honeycomb thermal insulation development, and assessment of pressurizer dynamics fitness to deal with operational transients and abnormal conditions as well. Related control issues like "Power – Temperature Program", and "Pressurizer Level Program" are also addressed by the CNEN team.

This paper, besides a very brief description of IRIS, will present a summary of CNEN activities in this project, concentrating on some of the more recent work dealing with operational transient analysis of the pressurizer behaviour. Finally, some of the management approach to such a large, world-wide design work force will also be addressed.

2. IRIS Conceptual Description

IRIS is a modular, integral, light water cooled, medium power [335 MW(e)/module] reactor which addresses the requirements of proliferation resistance, enhanced safety, improved economics and waste reduction. The 6.78m outside diameter by 21.4m in height IRIS integral vessel houses the reactor core, its support structures, upper internals, eight steam generators, internal shields, pressurizer and heaters, and eight reactor coolant pumps (Fig.1). Hot coolant rising from the reactor core to the top of the vessel is pumped into the steam generators annulus. The technical characteristics of IRIS are discussed in detail in references [2-7]. Its "safety by design" approach, where accidents are "designed out" to the maximum extent possible, instead of engineering to cope with their consequences is presented in [8].

Three most innovative features, which characterize IRIS project, are:

- Safety by design;
- Optimized maintenance; and,
- Long core life.

Safety by design

IRIS design takes advantage of the integral configuration to improve safety. Its configuration physically eliminates the possibility of many accidents to occur and also decreases the probability of occurrence and minimizes the consequences of the remaining ones. Fig. 1 shows the actual IRIS configuration. An IRIS first is the primary coolant pumps that are completely contained inside the vessel, thus eliminating any large vessel penetration and the possibility of secondary LOCAs.

The helical steam generators operate with superheated steam at the pressure of 5.8 MPa. The steam generators tubes operate in compression, since the primary water flows outside the tubes, thus steam generator tube rupture are less probable and its consequences are not as serious as in conventional SGs. Even in this case, the SGs are designed to withstand the primary system design pressure, and IRIS can operate with some SGs isolated in the case of tube failures.

The relatively high primary water mass, the low primary pressure drop and the high steam generators elevation enables enough natural circulation reducing the consequences of loss of flow accidents. The use of eight spool pumps inside the reactor vessel makes it possible to have a single locked rotor or pump seizure accidents without any core damage, moreover no reactor trip is needed from a safety point of view and the reactor could continue to operate at full power.

The IRIS pressure vessel is located inside a small spherical containment designed to a relatively high pressure. In the case of small or medium LOCA, the core remains covered for several days, or even weeks, depending on the natural heat removal over the containment external surface, without any emergency water injection. IRIS containment design makes use of suppression pools that are used also as a source of water gravity feed. For all analyzed accidents, the core remained covered. Further analyses are being made to show that IRIS can meet the requirement of "no need for off-site emergency response."

Optimized Maintenance

IRIS concept considers a long life core: *refuelling intervals are four years*. To take full advantage of this core life, in terms of capacity factor, this should be matched by a similar maintenance interval. Following a previous work by MIT and its application to IRIS conditions, only seven items were identified as still needing resolution to attain the 48 months interval and their resolution is currently being addressed.

IRIS designers plan to make use of all recent advances in on-line monitoring and diagnosis plus in-service inspection. It is planned to develop specific techniques for all critical reactor components. Actual tasks involve bi-lateral research projects proposed within the International Nuclear Energy Research Initiative of the DOE (I-NERI Program) and within the Brazilian Energy Fund of the Science and Technology Ministry. Artificial intelligence based systems are being studied to provide additional operational support [9].

The IRIS project also includes some "design for maintainability" requirement envisioning time reduction in the main maintenance activity. As an example, the replacement of a steam generator needs only the opening of the pressure vessel and the uncoupling of few lines and devices: it is an easy task that can be accomplished in a short time schedule.

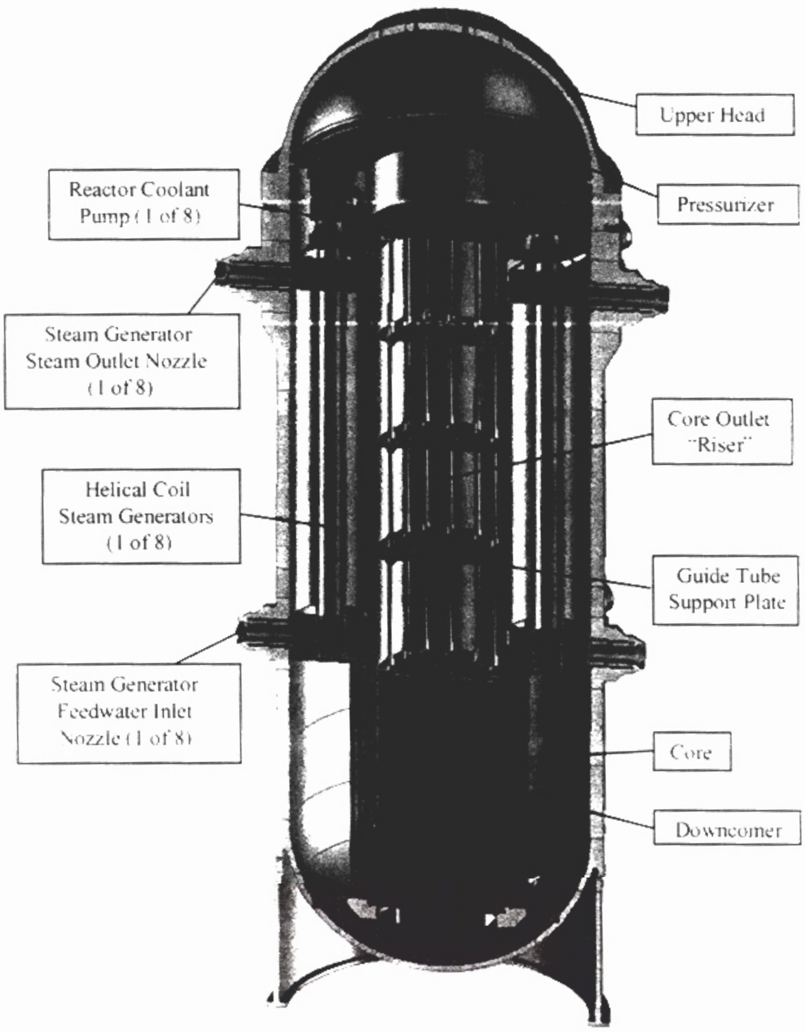

Figure 1. IRIS Integrated Primary Systems.

Long core life

An important approach to enhance proliferation resistance is to make the fuel less accessible by designing a core capable of operating in a straight burn long-cycle mode. IRIS considers a long life core: refuelling intervals can be as long as four years apart. Straight burn or partial refuelling shuffling cycles can be employed at the utility preference. This paper does not intend to present core design details, which can be found in references [10-11], which also presents links to more detailed references.

3. CNEN Activities in the IRIS Project

The main CNEN responsibility within the IRIS program is the internal pressurizer design and analyses. The design tasks for the pressurizer have included steam-water volume sizing, pressurizer to vessel physical separation by an internal thermal insulation, surge connections dimensioning and transient analyses, under different operating modes.

Since the signature of the collective agreement, the main tasks performed by the CNEN team have been:

- Conceptual design of the pressurizer, which includes the simplified transient analyses to evaluate the effectiveness of a steam bubble pressurizer, the conceptual design of the physical separation between the pressurizer saturated water and the reactor circulating water, the establishment of the safety valves set points, evaluation of heat losses from the pressurizer, specification of the heaters banks configuration, dimensioning of surge holes and re-circulation orifices of the pressurizer, study and definition of operational water levels;
- Development of a new RELAP 5 nodalization of the pressurizer;
- Development of simplified numerical tools to analyze operational transients, under different control options; and,
- Design experimental set-ups for the pressurizer study.

3.1. IRIS Internal Pressurizer Design

Pressurizer type IRIS is not a self-pressurized system like Otto Hahn [12] or CAREM [13]. The high elevation-pumps have NPSH requirements that preclude the possibility of having a saturated water layer over the core, which characterizes a self-pressurized reactor. Previous studies have demonstrated that the best choice in such case is a pressurizer design similar to conventional PWRs, a water-steam system, with the vapour formation accomplished by electric heaters. This was the system proposed for the Safe Integral Reactor (SIR) [14].

Pressurizer requirements The pressurizer satisfies a dual function; controlling the system pressure and providing the water interface needed to the control of the coolant inventory. The basis for sizing the pressurizer also establishes the boundaries and requirements for the pressurizer pressure control system and for the pressurizer water level control. It is sized to meet the following requirements:

- The combined saturated water and steam volumes must be sufficient to provide the desired pressure response to system volume changes
- The water volume must be sufficient to prevent a reactor trip during a step-load increase of plus or minus 10% of full power, with automatic reactor control
- The water volume must be sufficient to prevent the uncovering of the heaters following a reactor trip and turbine trip, with normal operation of the control system and no failures in the nuclear steam supply system
- The steam volume must be large enough to accommodate the surge resulting from a step load reduction from 100% to house load without reactor trip, assuming normal operation of the control system
- The steam volume must be large enough to prevent water relief through the safety valves following a complete loss of load with the high water level initiating a trip and with no steam dump available
- A low pressurizer pressure S-Signal shall not occur because of a reactor trip and turbine trip, assuming normal operation of control and makeup systems and no failures of the nuclear steam supply system

Preliminary studies by CNEN indicated that a conventional water-steam system could meet the pressurizing system requirements, without the need of costly R&D activities. These studies showed that, with a proper design, the relation of Pressurizer Volume to Reactor Power could be 3.4 times greater than a conventional 2-loop Westinghouse plant and almost 2.7 times greater than the AP600 advanced reactor. This gave enough margin to avoid the need of a spray system, which really would represent a challenging effort for the engineering team. Simplified transient analyses showed that the IRIS pressurizer basic design configuration without spray can withstand a high pressure-dimensioning transient of 100% load rejection, without reaching the design pressure, assuming shut down only on the high pressurizer pressure [15].

Pressurizer housing The IRIS pressurizer is within the reactor head, which, as a part of the pressure retaining wall of the reactor pressure vessel, is designed as a Class 1 vessel according to the ASME Code Section III. All penetrations of the closure head are located on the upper dome. There are 45 nozzles for control rod drive mechanisms (CRDMs), 90 nozzles for heating rods, and 48 instrumentation nozzles. The nozzles for the CRDMs and for the instrumentation tubes which extend through the head region have internal pipe extensions that go through the bottom plate.

Fig. 2 shows the pressurizer and how the saturated water is separated from the reactor circulating sub-cooled water by an internal structure with an "inverted hat shape". The function of this structure includes: (a) preventing the head closure flange and its seals from being exposed to the temperature difference between the reactor and pressurizer water, reducing thermal stresses and maintaining the sealing tightness; (b) providing some thermal insulation to reduce the heat transfer and maintain an adequate saturated water layer within the pressurizer; (c) providing structural support for the control rod drives mechanisms (CRDM) guides, core instrumentation tubes, and heaters; and (d) providing the communication flow paths between the reactor and pressurizer for surge and re-circulation flows.

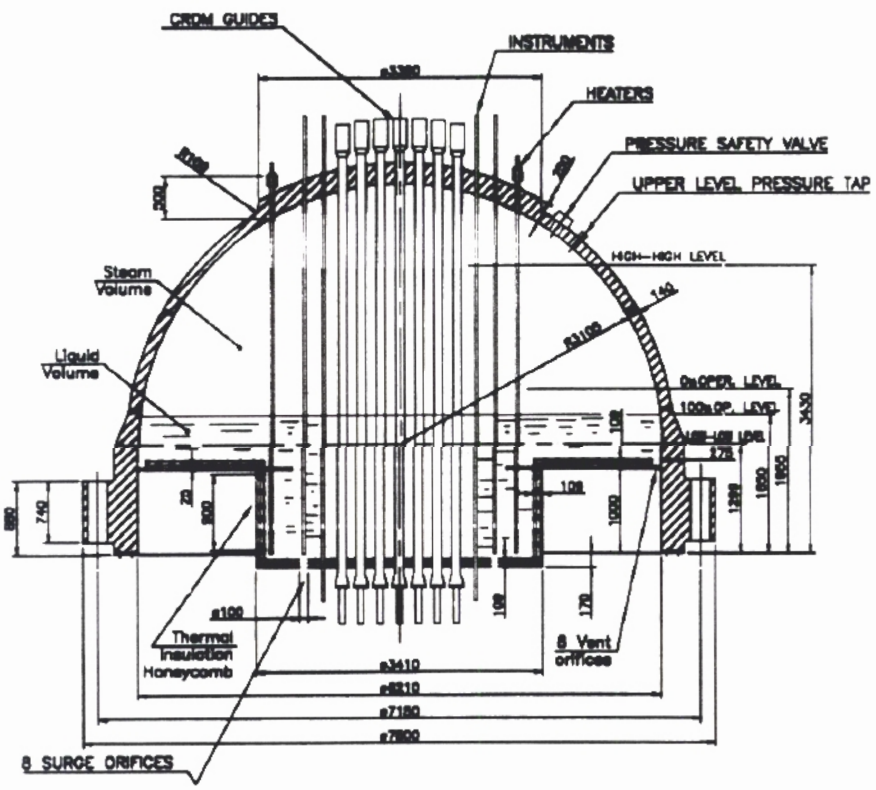

Figure 2. IRIS Integral Pressurizer.

Spray Analyses performed indicate that, after an in-surge transient, the return to pure steady state conditions is more sluggish than if a spray system were present. Simplified analyses of consecutive power steps had shown that this small unavoidable draw back of the current IRIS design does not affect the capability of the pressurizer to adequately cope, even when an out-surge operational transient happens after an in-surge transient. Thus, a conventional pressurizer spray capability is not necessary in the IRIS, however, special passive spray design concepts might be considered in future efforts to further improve the pressurizer performance.

Heaters The pressurizer heaters are designed to create and maintain the saturated water layer and to produce enough steam to limit the pressure decrease during transients of power increase. There are 90 electrical heaters providing a total heating power of 2430 kW. They are grouped in two banks, a proportional and a backup bank. A PI controller is proposed to control the proportional heater. The use of this controller can improve the pressurizer pressure response mainly during slow transients.

3.2. IRIS Internal Pressurizer Analyses

The requirements for the pressurizer sizing define a set of transients to be analyzed. Table I lists these IRIS design operating transients. This paper presents few results for one of them.

Table I. IRIS Design Operating Transients

Step Load changes of plus or minus 10% of full power
Ramp load increases and decreases of 5%/minute
Daily load follow operations: power ramp from 100 to 50% in 2 hours; operation at 50% power for 2 to 10 hours; power ramp from 50 to 100% in 2 hours; power remains at 100% for the remainder of a 24-hour cycle
Grid frequency response resulting in a maximum of 10% power changes at 2% per minute.
Full load rejection following a turbine trip

Transients that result in large and fast pressurizer in-surge were simulated and reported previously [15] to demonstrate the viability of the current pressurizer design without spray. Simplified adiabatic models and also more realistic RELAP5 mod3.3 models showed satisfactory results, allowing to go ahead with the present design solution. The ability to cope with very large in-surge transients was tested using some very demanding cases, e. g. full load rejection, with a 1s delayed shut down – after the occurrence of the high pressure signal – and a 4s delayed actuation of the Passive Emergency Heat Removal System (PEHRS) for decay heat removal. The pressure response in all cases remained within limits and, even with no credit for any power operated relief valves actuation, the safety valve pressure set point was not reached.

Although the thermal-hydraulic code chosen for the IRIS accident and transient analyses is the RELAP5 mod3.3, the model prepared for accident analyses does not have the normal operation controls needed for operational transients analyses. A simplified tool was developed for this purpose [16]. It was implemented using a set of interrelated MS Excel and Visual Basic macro programmed worksheets. It allows a quick review of the pressurizer data and execution of simplified transient analyses of its behaviour under different temperature/power programs, reactor and control characteristics, pressurizer level programs and volumetric control system capacities. Reactor kinetics were not modelled in the initial phase of the development of this tool, the transients are applied to the thermal power at the secondary side of the steam generators and the control were assumed to act direct on the reactor power, controlled within allowable rates of power change.

The pressure, level and reactor power controls used are similar to that of most conventional PWR reactors. The results presented here were obtained considering a partitioned sliding averaged temperature program (Fig. 3) and a pressurizer constant level program. Fig. 4 shows results for the initial part of the 10% negative step load transient, in terms of the steam generator (QSG) and the core thermal power (QR).

The control parameters used produced a fast and stable power response. The temperature results are in Fig. 5, where T_C is the mean core temperature, T_R is the riser temperature, T_{SG} is the mean steam generators temperature, T_D is the mean downcomer temperature. The behaviour of the pressurizer water level is shown in Fig. 6 and the pressure in Fig. 7. The pressure and temperature responses were fast and with a stable convergence to the programmed values without overshoot. The results showed excellent pressure smoothing capability of the pressurizer.

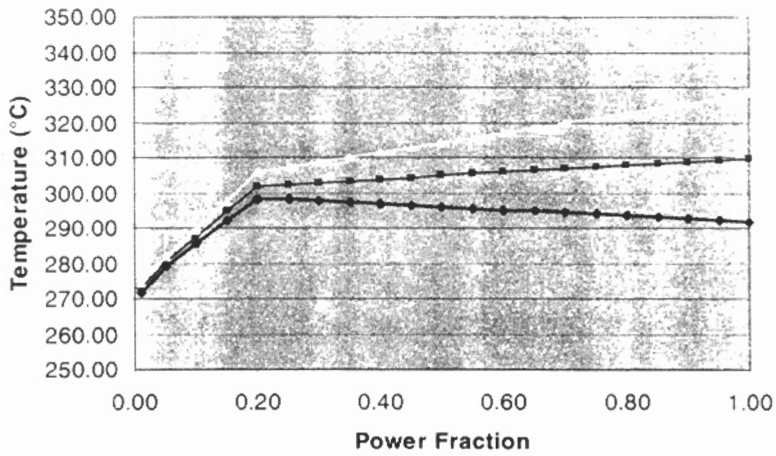

Figure 3. Sliding T Average Program.

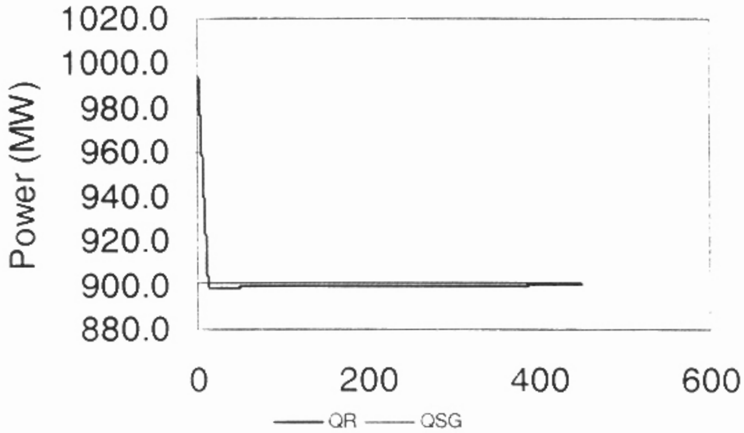

Figure 4. Step Load of –10%: Power response.

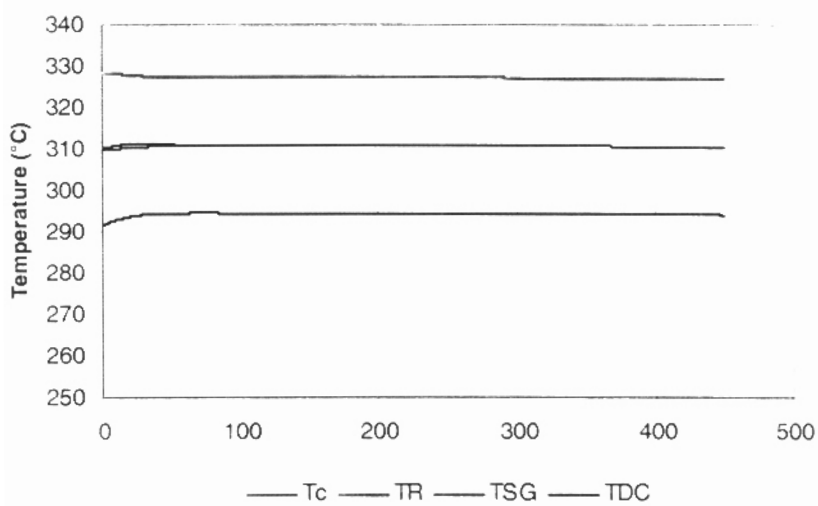

Figure 5. Step Load of –10%: Temperature.

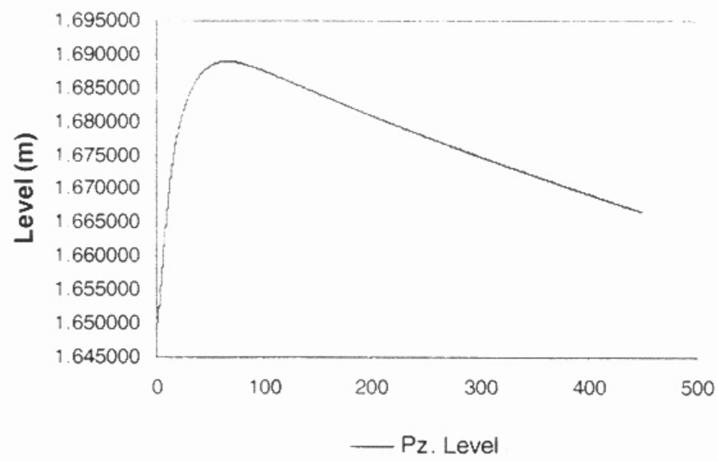

Figure 6. Step Load of –10%: Level.

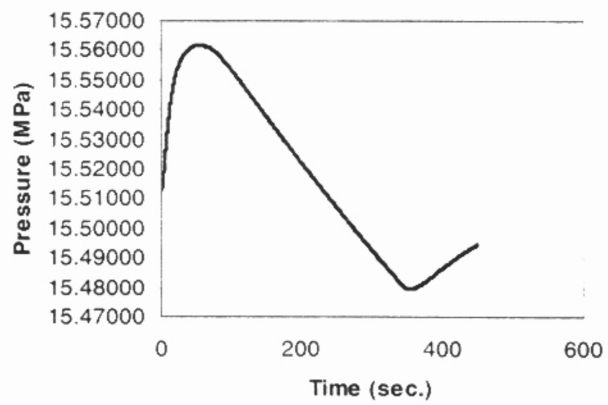

Figure 7. Step Load of –10%: Pressure.

4. IRIS Consortium Management Issues

The self-sustained activity of the IRIS consortium partners, has greatly exceeded the work scope originally scheduled in response to the DOE NERI request for proposal. Essentially, the difference resulted to be between conducting an exploratory investigation of a concept feasibility versus initiating a real design focussed towards commercial feasibility. Items like component characterization or site layouts were never considered in the proposal but they are addressed here at length.

Managing a consortium comprising 22 organizations from nine countries, which vary from industry to academia, to research laboratories and power producers, and span 7 languages and 17 time zones is a challenge to say the least. However the IRIS Consortium is held together and thrives because:

- All members share the belief that the IRIS concept can contribute significantly to the forthcoming nuclear renaissance and are firmly committed to see it happening; and,
- The unique IRIS concept where all members of the consortium, regardless of the level of their individual contributions, are "owners" of IRIS and share all information and decisions.

The diversity in culture and technical background and objectives is turned into a positive thrust by providing different viewpoints through the operation of multi-organization teams. In the case of CNEN for example, CNEN leads and integrates the contributions of Westinghouse and Oak Ridge National Laboratory to the pressurizer design. For the RELAP analyses, CNEN provides an independent verification to the input file preparation by the University of Zagreb, Croatia. This represents a necessary contribution to the verification and validation of one of the major computer codes used in the IRIS safety analyses. In addition to the operation of multiple working groups, the entire IRIS team meets twice a year, once in the US and once at one of the overseas members, to review work in progress, outline future work and discuss/resolve technical and programmatic issues.

Working on a new program being developed at a brisk pace by an international team is an extremely exciting endeavour enjoyed by all team members, but it carries a few practical drawbacks. A part from the quite heavy coordination burden on the program manager, it resulted in the following "glitches" which must be brought to the attention:

— With the work proceeding in parallel at various establishments, the length of the various tasks being different and the design philosophy and design characteristics (core fuel lifetime, power rating, configuration, etc.) changing, it happened that at times different members of the consortium were working on different design versions.

— Quite an effort has been exercised in trying to homogenize the writing style of so many different contributions and mother tongues.

— Preparing and issuing annual reports takes an enormous amount of time. We believe that it was well worth to document to the best of our abilities all the work performed by the IRIS consortium.

The coordination of each national team presents similar problems. The Brazilian Team coordination was not an easy task. Regional differences, the concurrence of several different tasks, the integration of people from research institutes and factory and also the limited funds for such activities are the main difficulties. The key to keep a highly motivated team sets in the maintenance of a high level of research demand accompanied by frequent meetings and the offer of international knowledge exchange. The need for the edition of two annual reports to be presented during the two annual international meetings is almost enough to establish the high level in research demand.

During the time that elapsed from the agreement signature, it was observed that such kind of project allows the improvement of the Brazilian nuclear knowledge, once the research and engineering teams are kept involved with activities shared with the most advanced teams from developed countries. We feel that this project has the capability of expanding the present level of deployment of nuclear technology in Brazil.

5. Conclusions

This paper presented a very brief description of IRIS, with emphasis in its "safety by design approach." A summary of the Brazilian activities in the IRIS project, coordinated by CNEN, was presented. Some of the management issues concerning this large and geographically dispersed design work force was also addressed, demonstrating that such approach of international project immediately found a positive resonance, as the IRIS team kept growing over its three-year life from the initial four members and two countries to the present over 22 members from nine countries.

The IRIS project represents the latest evaluation of the light water reactors, which are by far the predominant type of nuclear reactors world-wide. Its technical, economic and programmatic characteristics, position IRIS to be a very significant contributor to nuclear power production in the 21st century. Its innovative approach to international, co-operative management enables IRIS to be deployable world-wide. Brazil recognizes that IRIS can be an important component of its nuclear portfolio and is contributing to IRIS development, including a leading role in the pressurizer design and analysis.

The pressurizer is a significant component of the IRIS safety by design approach by intrinsically smoothing the response to overpressure transients and of its design simplification, by making sprays unnecessary. Analyses performed by CNEN and summarized here confirm the robustness of the IRIS pressurizer design.

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